

# Air Mass Origin in the Arctic and its Response to Future Warming

Clara Orbe  
NASA Postdoctoral Fellow

Paul A. Newman, Darryn W. Waugh, Mark Holzer, Luke Oman,  
Lorenzo M. Polvani, Feng Li



# Motivation

Arctic climate is **closely linked to Northern Hemisphere (NH) midlatitudes** through the long-range transport of pollutants:

# Motivation

Arctic climate is **closely linked to Northern Hemisphere (NH) midlatitudes** through the long-range transport of pollutants:

- **Chemistry:** The springtime buildup of halocarbons from midlatitudes initiates rapid springtime **ozone production** [*Atlas et al. (2003), Klonecki et al. (2003)*]
- **Radiation:** Increased black carbon deposition on snow and ice has reduced albedos in recent decades enhancing what “amplified” warming (*Hansen and Nazarenko (2004)*).

# Motivation

Long-range pollution transport into the Arctic has long been linked to the **large-scale circulation** in terms of blocking events (*Raatz and Shaw (1984), Iversen and Joranger (1985)*) and variability patterns like the North Atlantic Oscillation (*Eckhardt et al. (2003), Duncan and Bey (2004)*).

# Motivation

Long-range pollution transport into the Arctic has long been linked to the **large-scale circulation** in terms of blocking events (*Raatz and Shaw (1984), Iversen and Joranger (1985)*) and variability patterns like the North Atlantic Oscillation (*Eckhardt et al. (2003), Duncan and Bey (2004)*).

Comprehensive climate models project **changes in the large scale circulation** over NH midlatitudes:

- poleward and upward shift midlatitude tropospheric jets (e.g. *Yin (2005), Chang et al. (2012), Barnes and Polvani (2013)*)
- expansion and weakening of the Hadley Cell (e.g., *Lu et al. (2007)*)

# Motivation

Long-range pollution transport into the Arctic has long been linked to the **large-scale circulation** in terms of blocking events (*Raatz and Shaw (1984), Iversen and Joranger (1985)*) and variability patterns like the North Atlantic Oscillation (*Eckhardt et al. (2003), Duncan and Bey (2004)*).

Comprehensive climate models project **changes in the large scale circulation** over NH midlatitudes:

- poleward and upward shift midlatitude tropospheric jets (e.g. *Yin (2005), Chang et al. (2012), Barnes and Polvani (2013)*)
- expansion and weakening of the Hadley Cell (e.g., *Lu et al. (2007)*)

And yet, the **transport response to future warming** in the Arctic has not been assessed ...

# Underlying Uncertainties in Transport

Recent multi-model comparisons show that **uncertainties in transport into the Arctic** affect models' representations of black carbon, tropospheric ozone, and carbon monoxide (*Shindell et al. (2008)*).

# Underlying Uncertainties in Transport

Recent multi-model comparisons show that **uncertainties in transport into the Arctic** affect models' representations of black carbon, tropospheric ozone, and carbon monoxide (*Shindell et al. (2008)*).

Transport uncertainties linger partly because of the lack of available diagnostics that completely **disentangle transport from emissions and chemistry**:

- “CO” tracers in *Klonecki et al. (2003)* and *Shindell et al. (2008)* reflect the interaction of transport with realistic CO emissions and/or a 50-day chemical lifetime
- Not feasible for assessing transport responses to long-term changes in climate (e.g. Lagrangian particle trajectory calculations in *Stohl et al. (2005)*)



# Underlying Uncertainties in Transport

Recent multi-model comparisons show that **uncertainties in transport into the Arctic** affect models' representations of black carbon, tropospheric ozone, and carbon monoxide (*Shindell et al. (2008)*).

Transport uncertainties linger partly because of the lack of available diagnostics that completely **disentangle transport from emissions and chemistry**:

- “CO” tracers in *Klonecki et al. (2003)* and *Shindell et al. (2008)* reflect the interaction of transport with realistic CO emissions and/or a 50-day chemical lifetime
- Not feasible for assessing transport responses to long-term changes in climate (e.g. Lagrangian particle trajectory calculations in *Stohl et al. (2005)*)

As it stands, therefore, **a tracer-independent measure of the climatological transport from NH midlatitudes to the Arctic** is sorely needed.

# Diagnosing Transport into the Arctic: Air Mass Origin

A simple transport measure is the origin of air in the Arctic with respect to the planetary boundary layer (PBL).

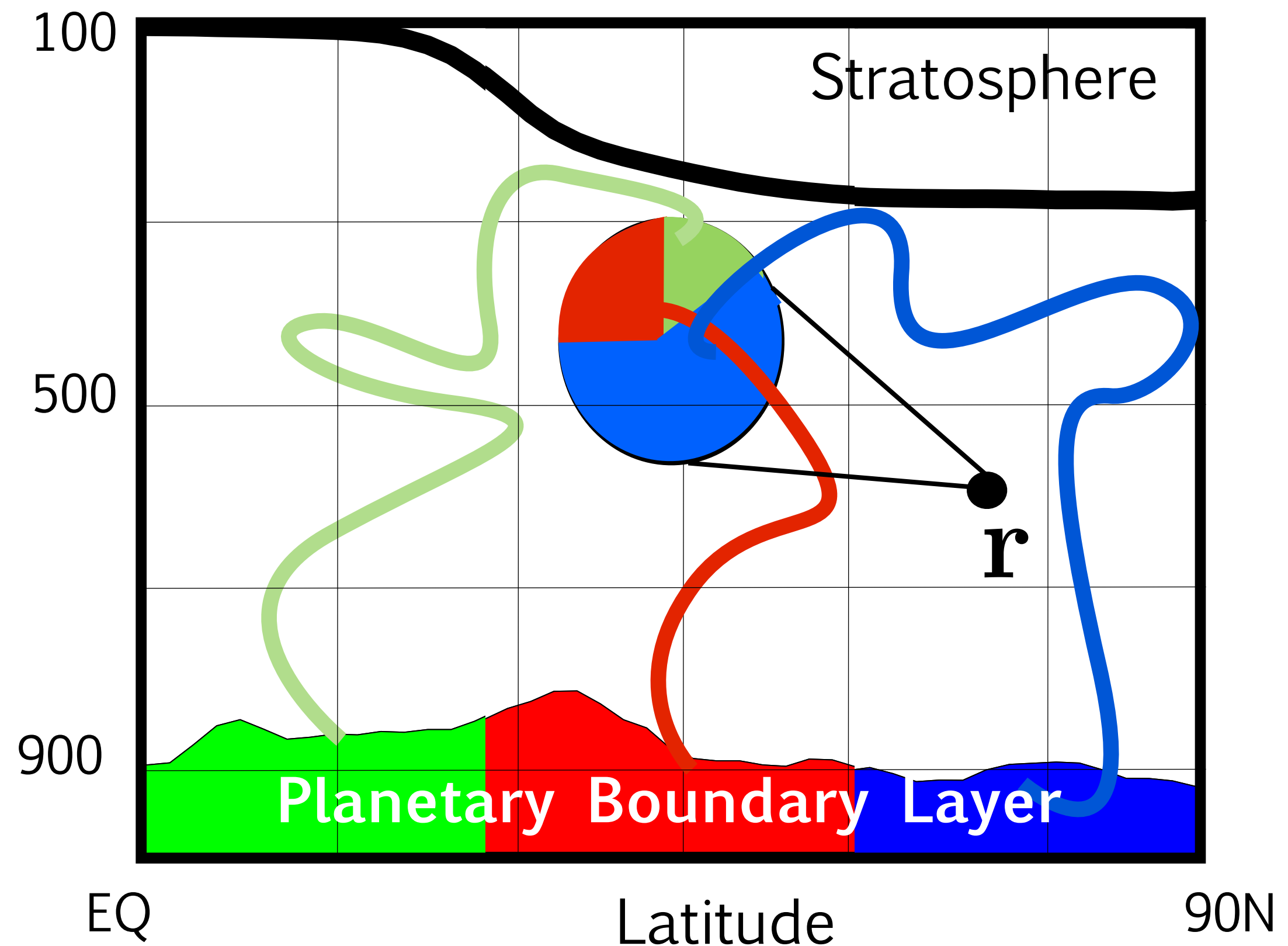
# Diagnosing Transport into the Arctic: Air Mass Origin

For example, air that last contacts the oceans is **relatively depleted in aerosols** compared to air that originates over midlatitudes (i.e. industrial emissions).

# Diagnosing Transport into the Arctic: Air Mass Origin

The air mass fraction  $f(\mathbf{r}|\Omega_i)$  is the fraction of air at location  $\mathbf{r}$  that last contacted the planetary boundary layer at  $\Omega_i$ .

$\Omega_i$  = PBL origin region



# Diagnosing Transport into the Arctic: Air Mass Origin

In practice, the air mass fraction  $f(\mathbf{r}|\Omega_i)$  is calculated as:

$$\begin{aligned}(\partial_t + \mathcal{T})f(\mathbf{r}, t|\Omega_i) &= 0 \\ f &= 1 \text{ in } \Omega_i \text{ and } f = 0 \text{ in } \Omega_i^c\end{aligned}$$

$$\Omega_i \equiv \text{origin region} \qquad \Omega_i^c \equiv \text{everywhere else in PBL}$$

At equilibrium:

$$f(\mathbf{r}, t|\Omega_i) \rightarrow f(\mathbf{r}|\Omega_i)$$

# Diagnosing Transport into the Arctic: Air Mass Origin

In practice, the air mass fraction  $f(\mathbf{r}|\Omega_i)$  is calculated as:

$$(\partial_t + \mathcal{T})f(\mathbf{r}, t|\Omega_i) = 0$$
$$f = 1 \text{ in } \Omega_i \text{ and } f = 0 \text{ in } \Omega_i^c$$

$$\Omega_i \equiv \text{origin region} \quad \Omega_i^c \equiv \text{everywhere else in PBL}$$

The air mass fraction is a complete diagnostic in that it captures the **integrated (advective + diffusive)** information about the circulation.

# Diagnosing Transport into the Arctic: Air Mass Origin

In practice, the air mass fraction  $f(\mathbf{r}|\Omega_i)$  is calculated as:

$$\begin{aligned} (\partial_t + \mathcal{T})f(\mathbf{r}, t|\Omega_i) &= 0 \\ f &= 1 \text{ in } \Omega_i \text{ and } f = 0 \text{ in } \Omega_i^c \end{aligned}$$

$$\Omega_i \equiv \text{origin region} \qquad \Omega_i^c \equiv \text{everywhere else in PBL}$$

Because the air has to contact the PBL *somewhere*, it follows that:

$$\text{For } \Omega_i \text{ that span the entire PBL: } \sum_i f(\mathbf{r}|\Omega_i) = 1$$

# Experimental Setup

## Model:

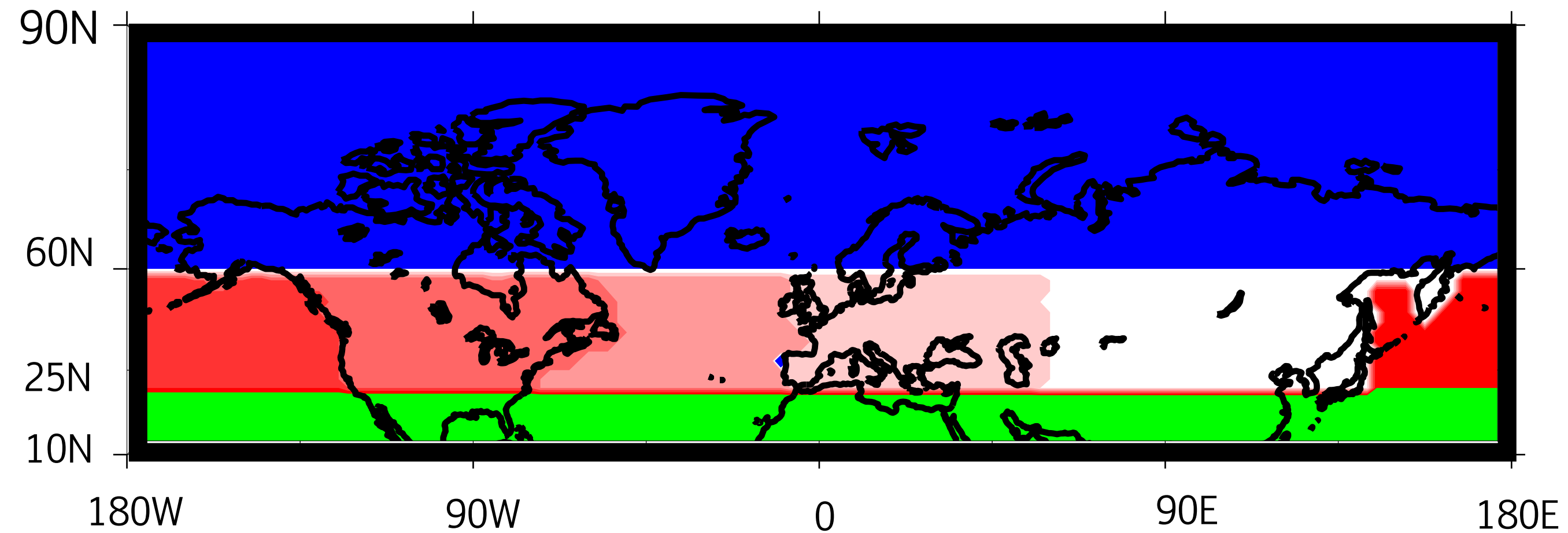
- GEOSCCM: GEOS-5 atmospheric general circulation model [*Rienecker et al. (2008)*] with comprehensive stratospheric chemistry [*Douglass et al. (1996)*]
- Resolution:
  - 2° latitude x 2.5° longitude;
  - 72 levels, 23 spanning 1-100 hPa
- Semi-Lagrangian flux form advection [*Lin and Rood (1996)*]
  - No explicit tracer diffusion

## Tracers:

9  $f(\mathbf{r}, t | \Omega_i)$  tracers for 9  $\Omega_i$  origin regions.



$\Omega_i \equiv$  origin region



$\Omega_{ARC}$

[60°N, 90°N]

$\Omega_{MID}$

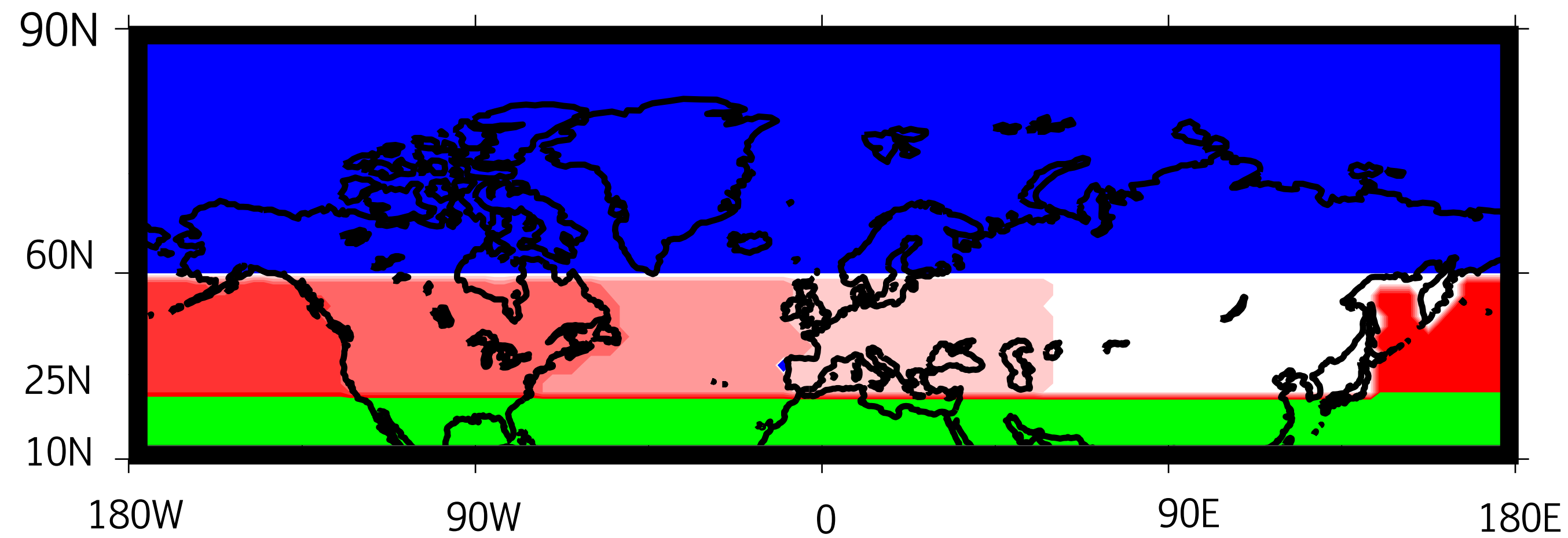
[25°N, 60°N]

$\Omega_{STH}$

[25°N, 90°S]

$$\sum_i f(\mathbf{r}|\Omega_i) = 1$$

$\Omega_i \equiv$  origin region



ocean regions:  $\Omega_{\text{EPAC}}$   $\Omega_{\text{ATL}}$   $\Omega_{\text{WPAC}}$

land regions:  $\Omega_{\text{NAM}}$   $\Omega_{\text{EUR}}$   $\Omega_{\text{ASI}}$

$$\sum_i f(\mathbf{r}|\Omega_i) = f(\mathbf{r}|\Omega_{\text{MID}})$$

# Model Integrations

- Two 20-year time-slice integrations:

SSTs and sea ice concentrations taken from a NCAR CCSM run forced with A1B greenhouse gases (GHGs) and A1 ozone-depleting substances (ODS)

REF: “2000-2019” averages

A1B: “2080-2099” averages

# Model Integrations

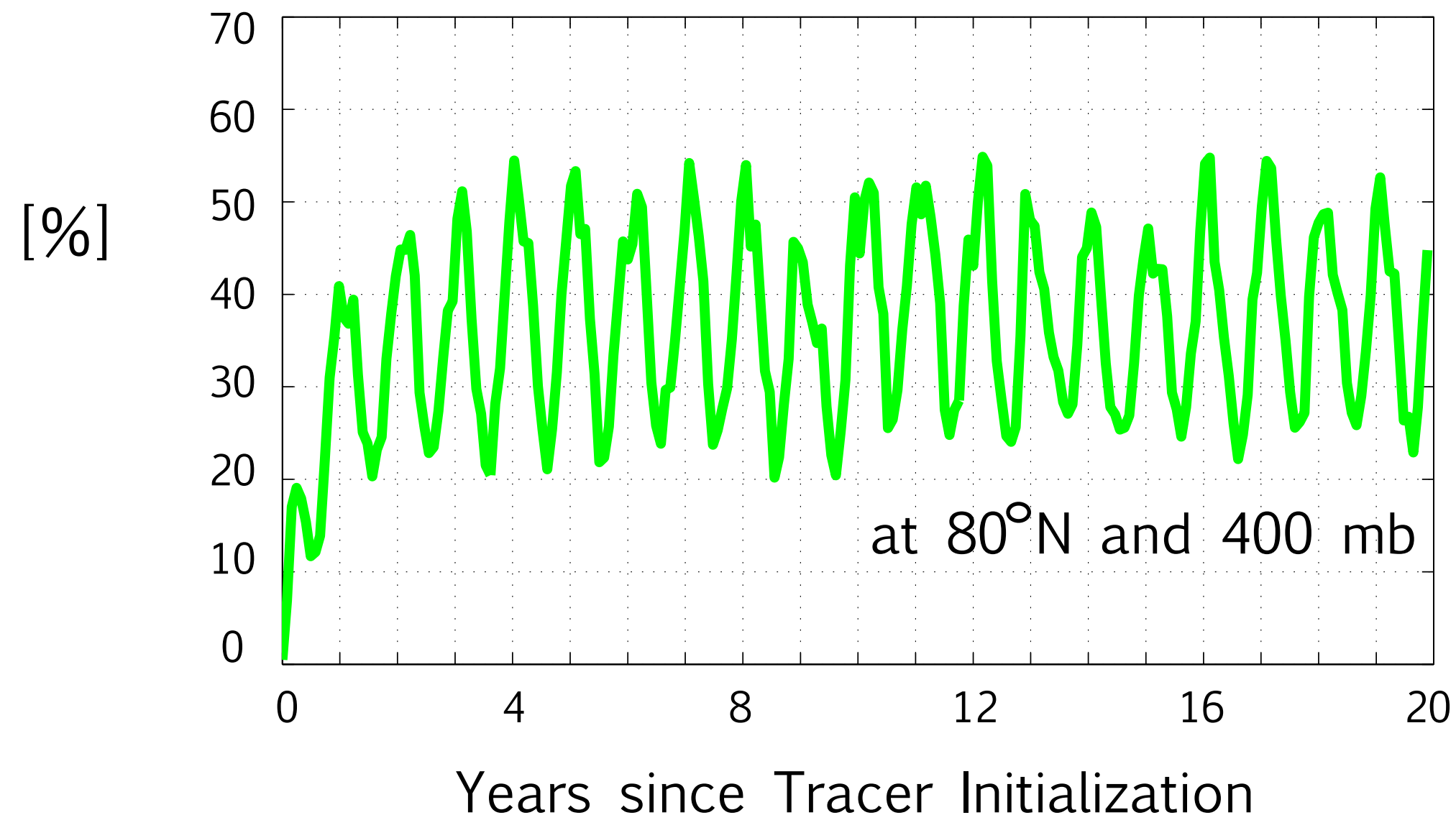
- Two 20-year time-slice integrations:

SSTs and sea ice concentrations taken from a NCAR CCSM run forced with A1B greenhouse gases (GHGs) and A1 ozone-depleting substances (ODS)

REF: “2000-2019” averages

A1B: “2080-2099” averages

Air Mass Fraction  $f(\mathbf{r}, t | \Omega_{\text{STH}})$



# Model Integrations

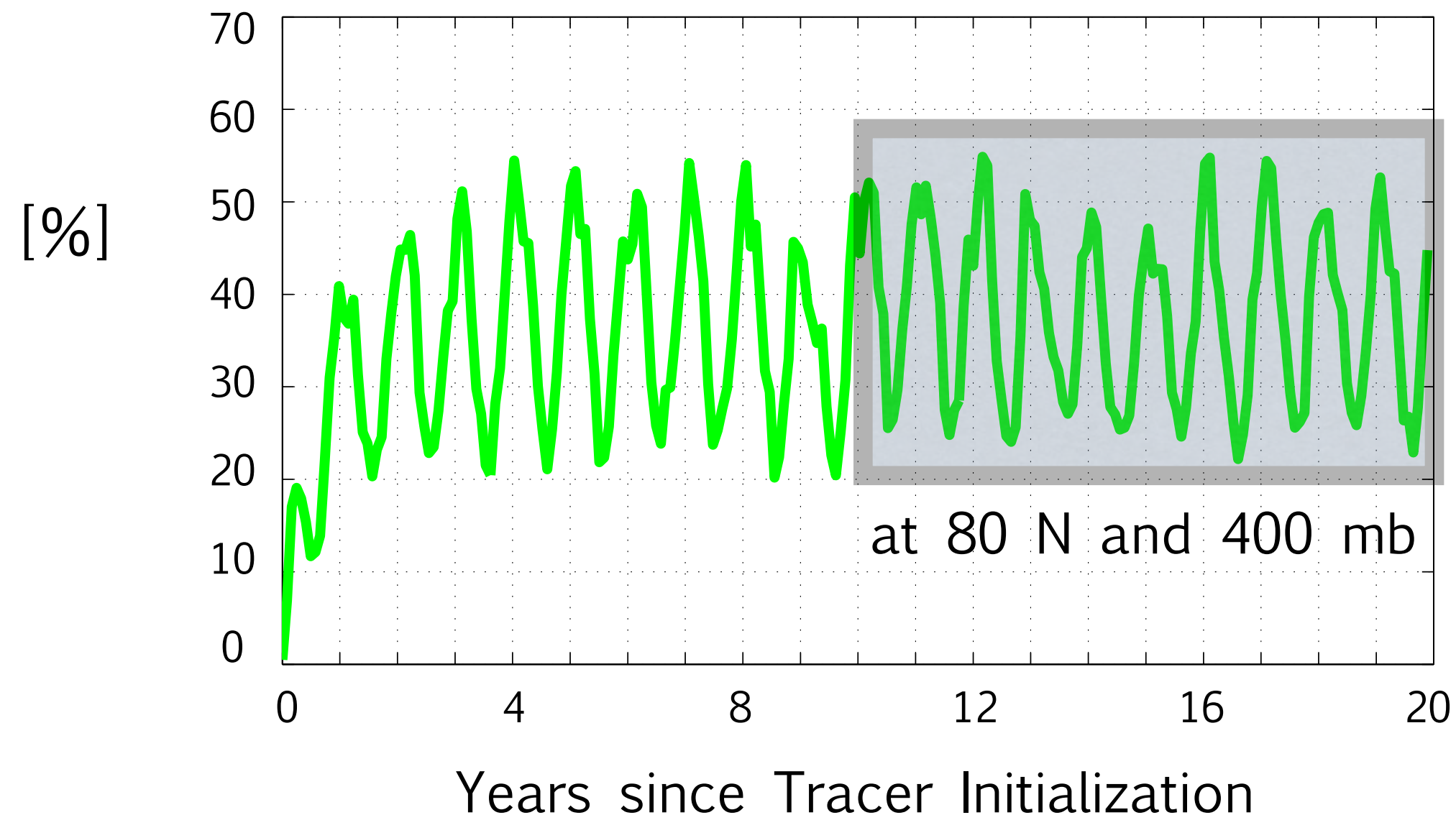
- Two 20-year time-slice integrations:

SSTs and sea ice concentrations taken from a NCAR CCSM run forced with A1B greenhouse gases (GHGs) and A1 ozone-depleting substances (ODS)

REF: “2000-2019” averages

A1B: “2080-2099” averages

Air Mass Fraction  $f(\mathbf{r}, t | \Omega_{\text{STH}})$



At equilibrium:

$$f(\mathbf{r}, t | \Omega_i) \rightarrow \bar{f}(\mathbf{r} | \Omega_i)$$

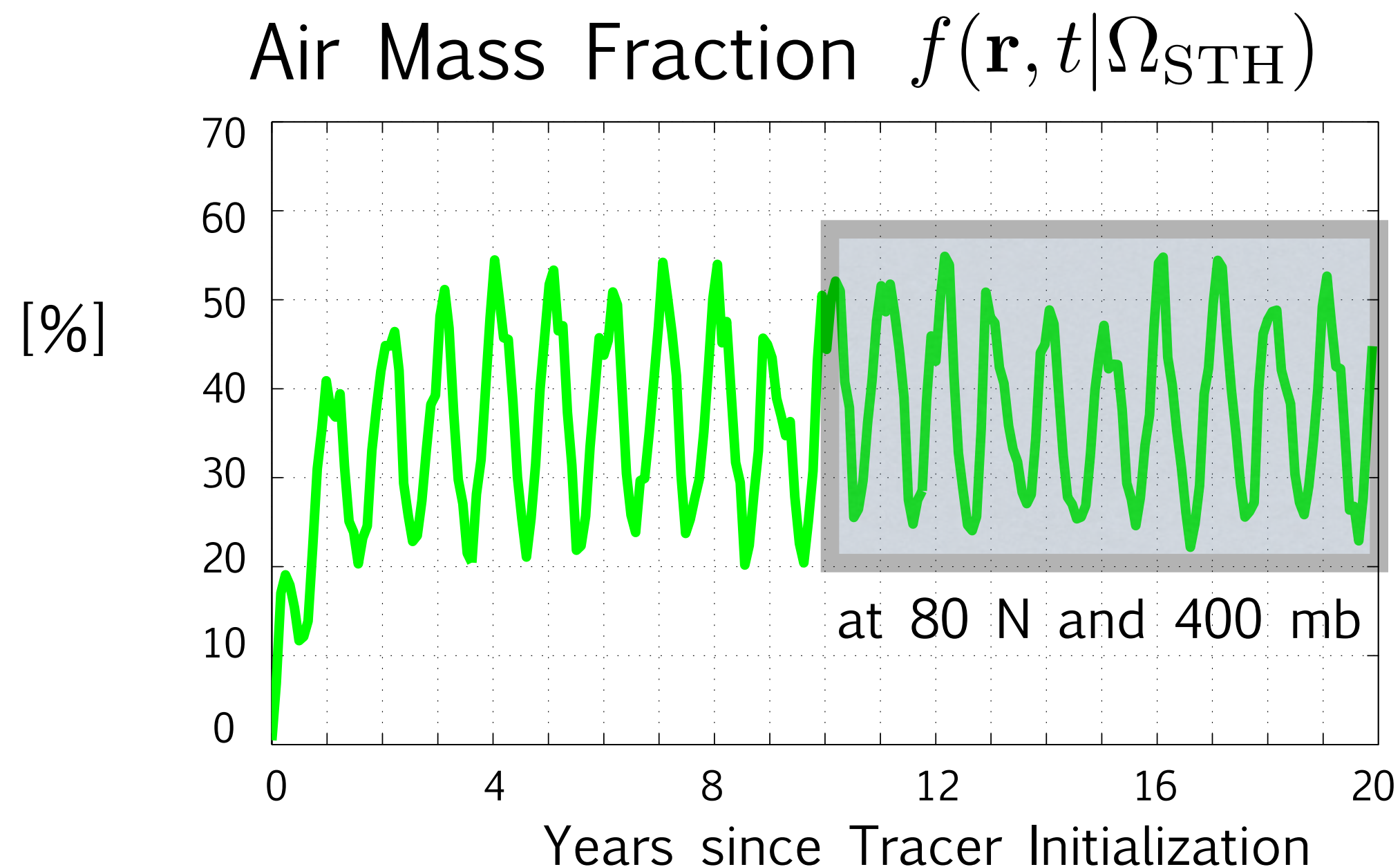
# Model Integrations

- Two 20-year time-slice integrations:

SSTs and sea ice concentrations taken from a NCAR CCSM run forced with A1B greenhouse gases (GHGs) and A1 ozone-depleting substances (ODS)

REF: “2000-2019” averages

A1B: “2080-2099” averages



Climate Change:

$$\Delta = \text{A1B} - \text{REF}$$



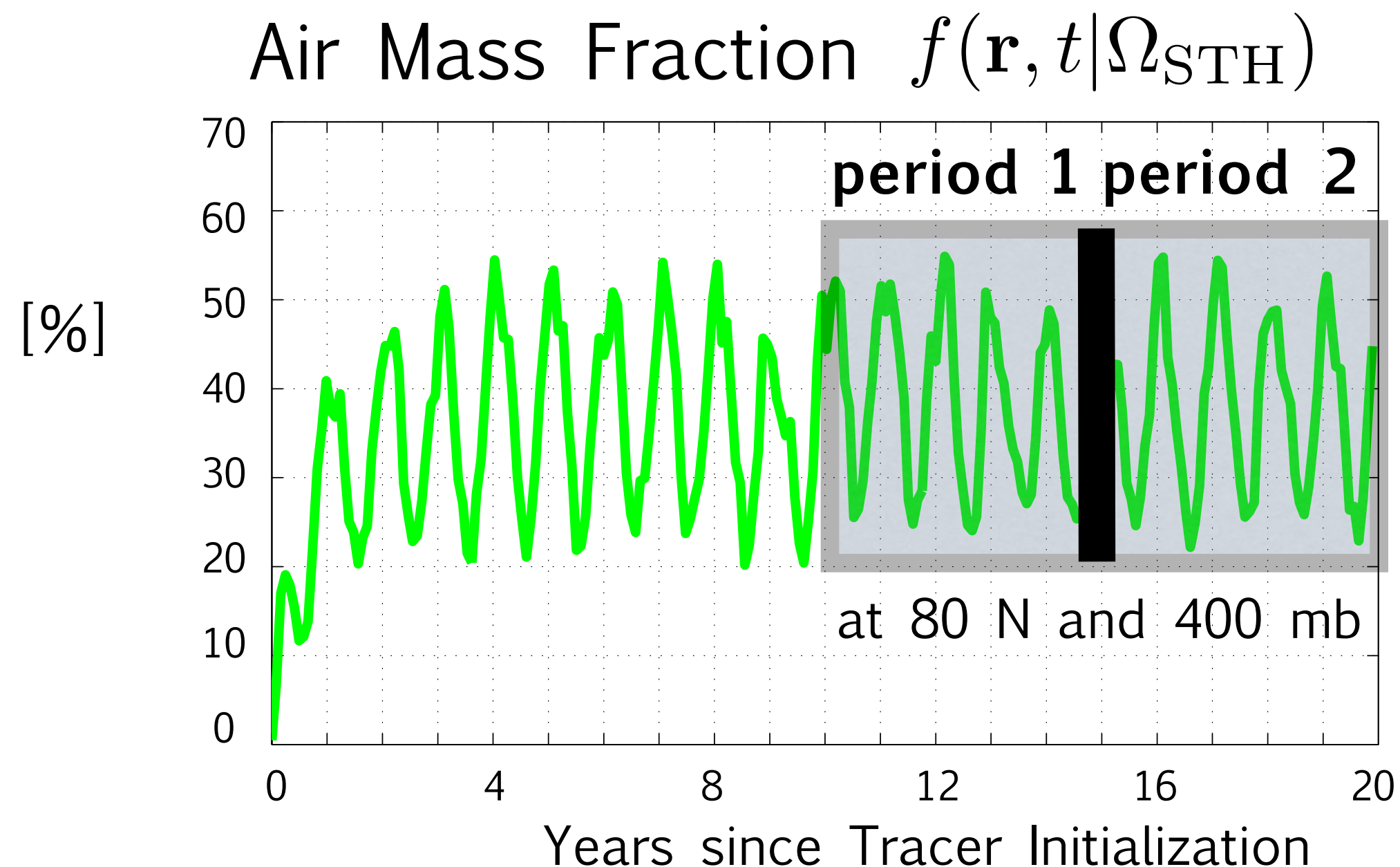
# Model Integrations

- Two 20-year time-slice integrations:

SSTs and sea ice concentrations taken from a NCAR CCSM run forced with A1B greenhouse gases (GHGs) and A1 ozone-depleting substances (ODS)

REF: “2000-2019” averages

A1B: “2080-2099” averages

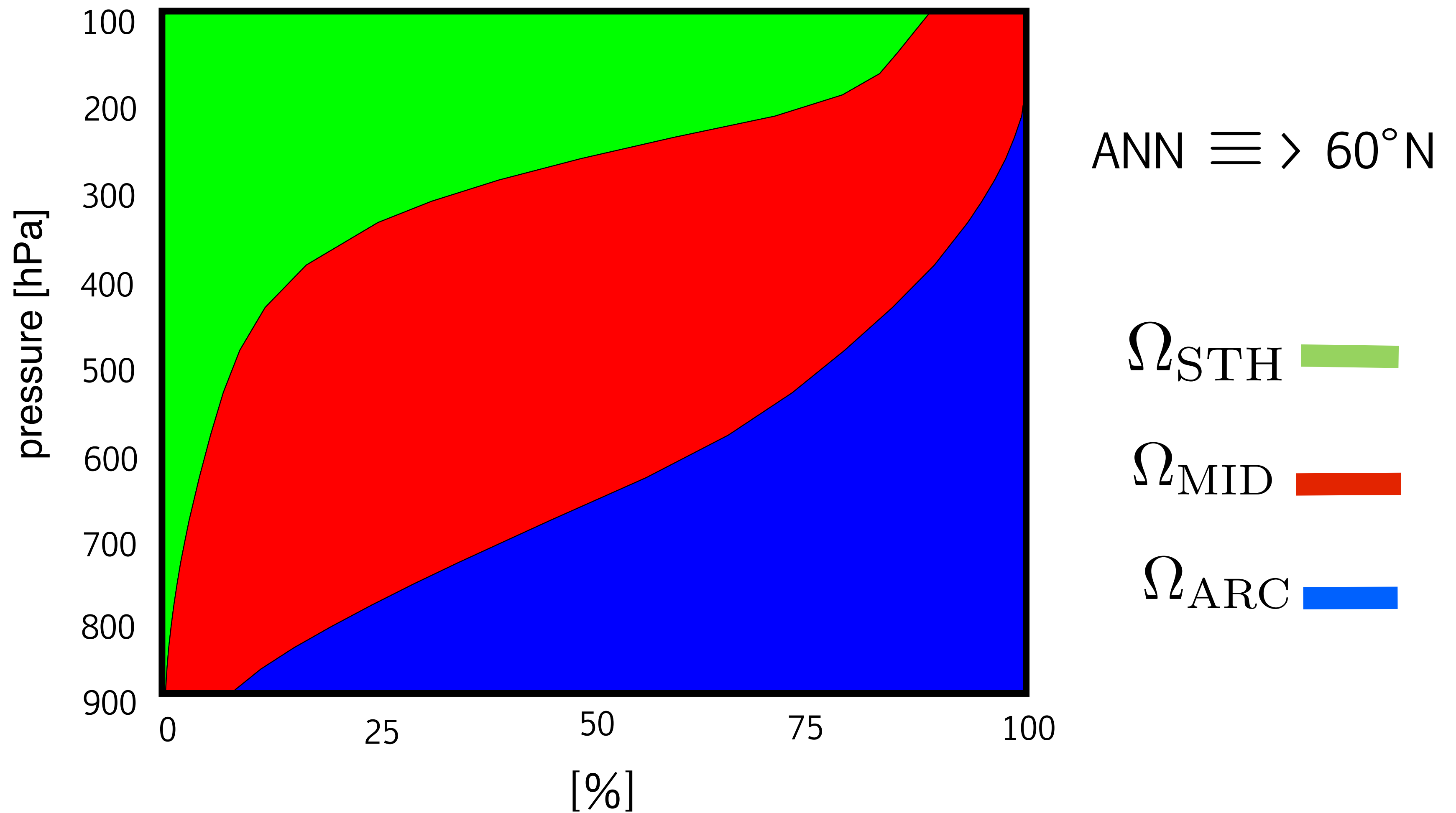


Significance assessed relative to:

$$\delta = \text{period 1} - \text{period 2}$$

# Annual Mean Arctic Air Mass Fraction

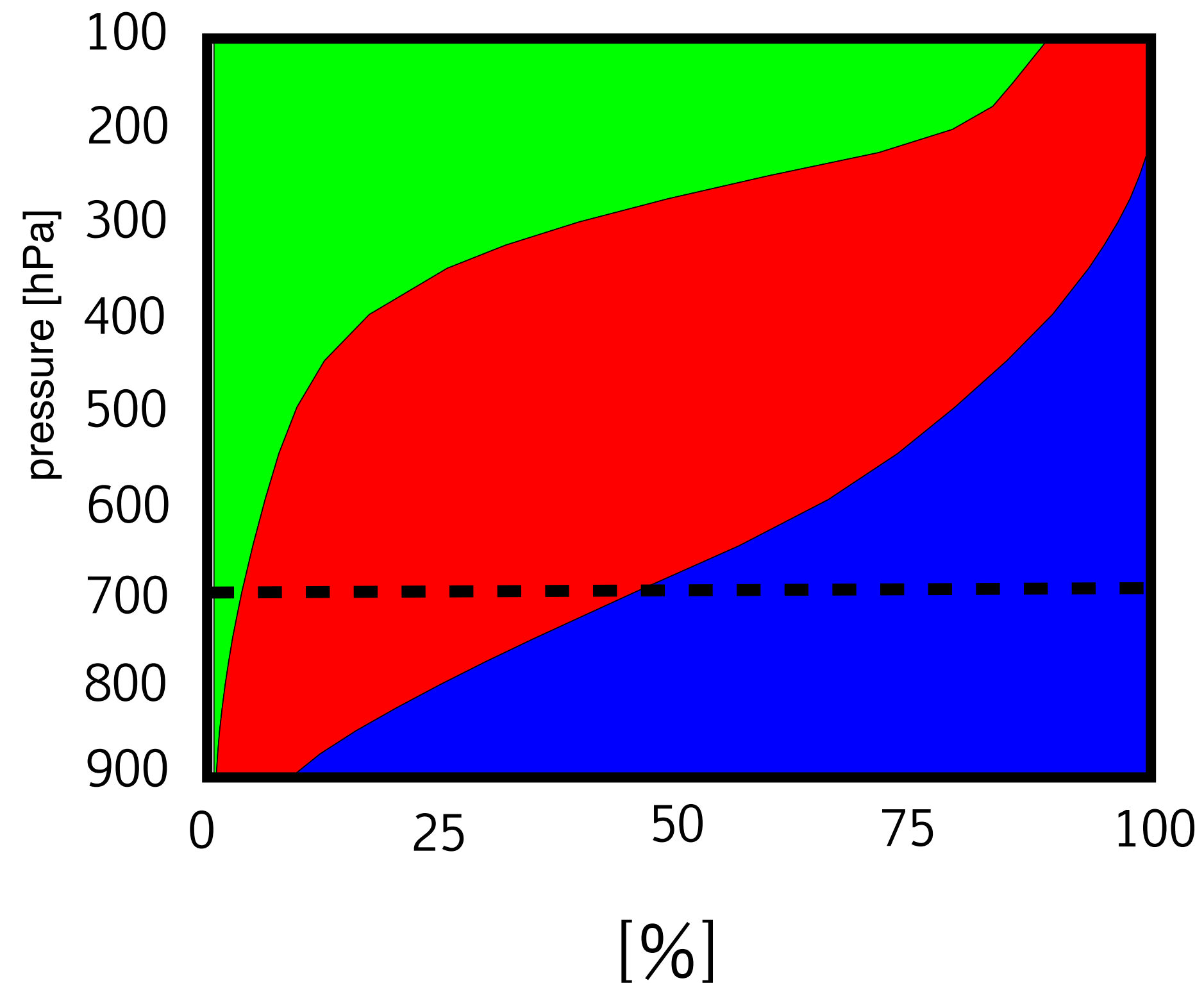
$$\overline{f}_{\text{ARC}}^{\text{ANN}}(p|\Omega_i)$$



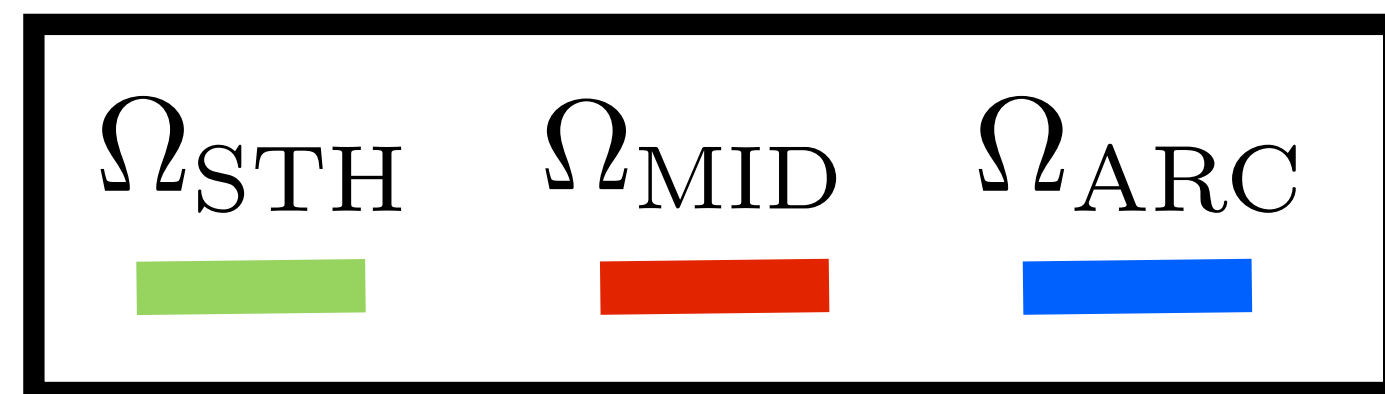


# Annual Mean Arctic Air Mass Fraction

$$\overline{f}_{\text{ARC}}^{\text{ANN}}(p|\Omega_i)$$

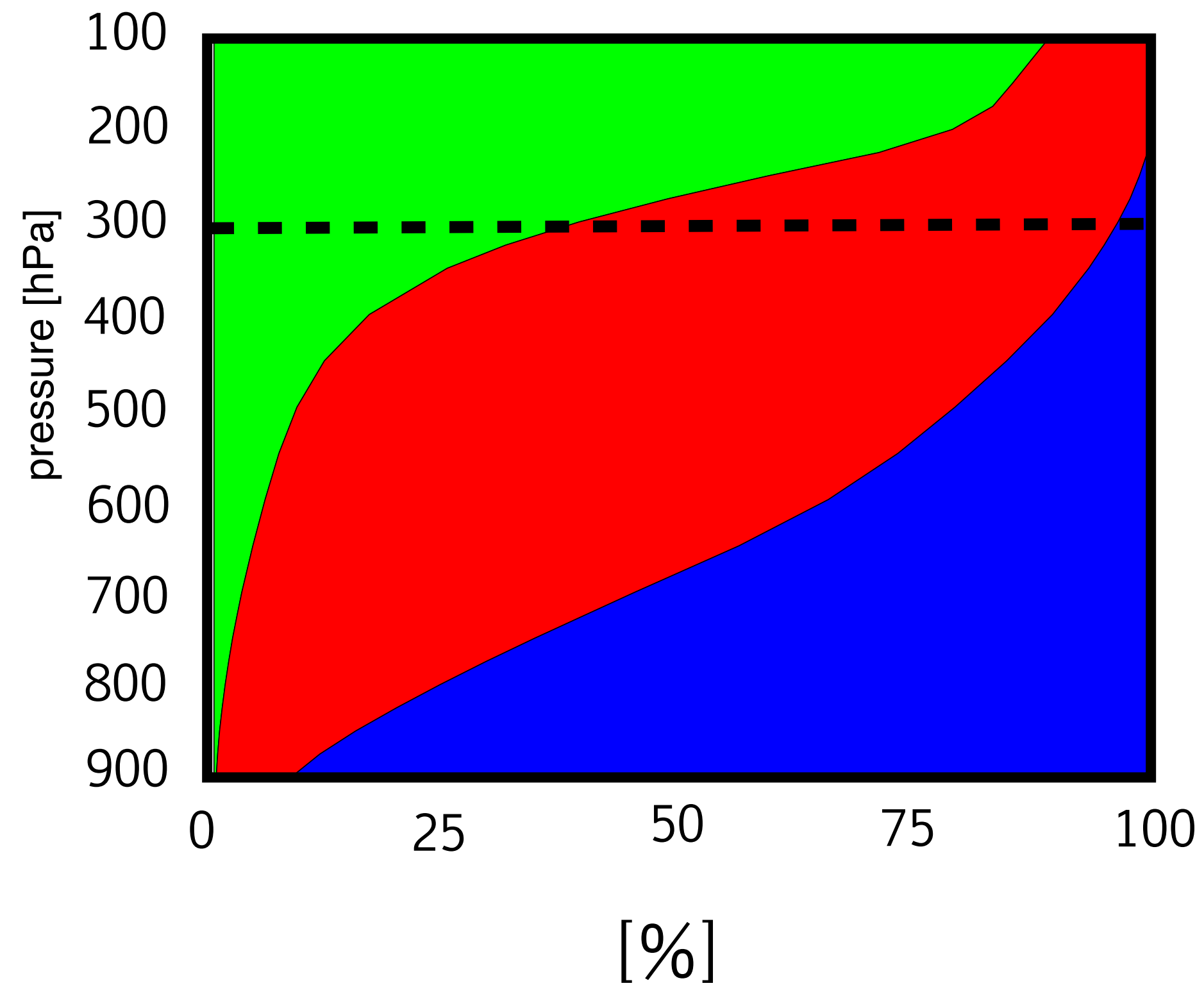


Below 700 mb the largest fractions originate over the Arctic (i.e. air trapped in “polar dome” (Klonecki *et al.* (2003), Law and Stohl (2007)).

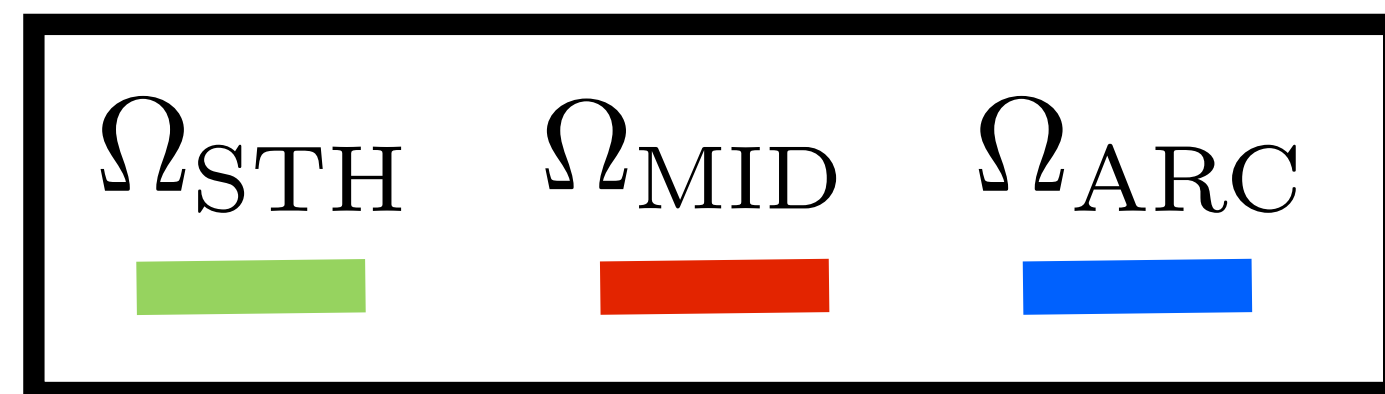


# Annual Mean Arctic Air Mass Fraction

$$\overline{f}_{\text{ARC}}^{\text{ANN}}(p|\Omega_i)$$

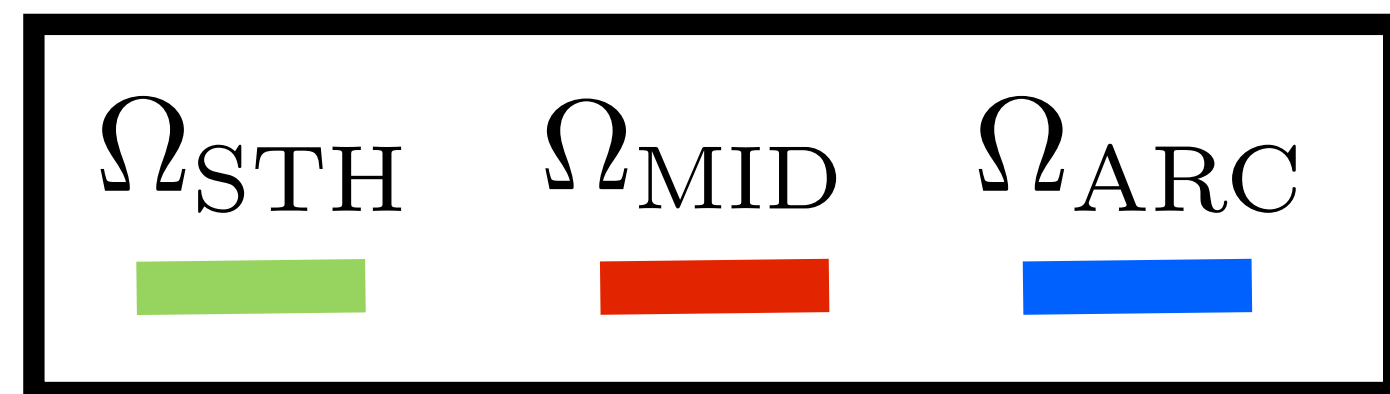
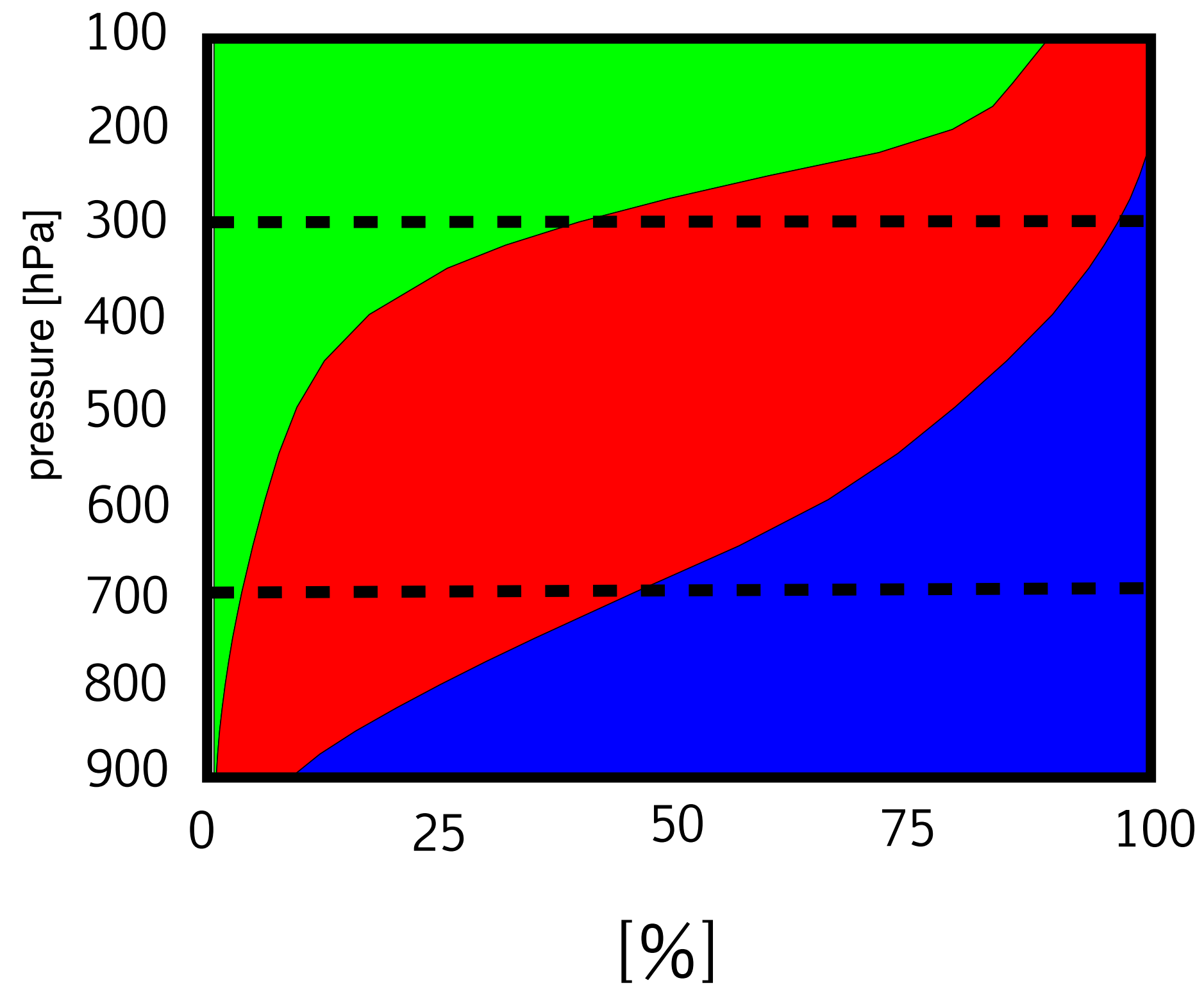


Above 300 mb (tropopause) the largest fractions originate south of 25°N (i.e. air enters the stratosphere at the tropical tropopause and is quasi-horizontally transported to high latitudes)



# Annual Mean Arctic Air Mass Fraction

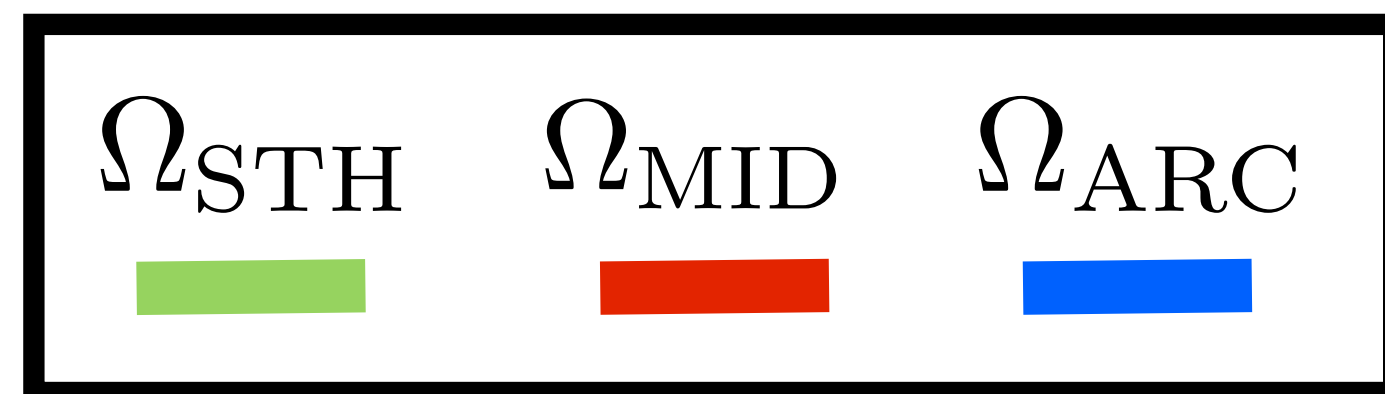
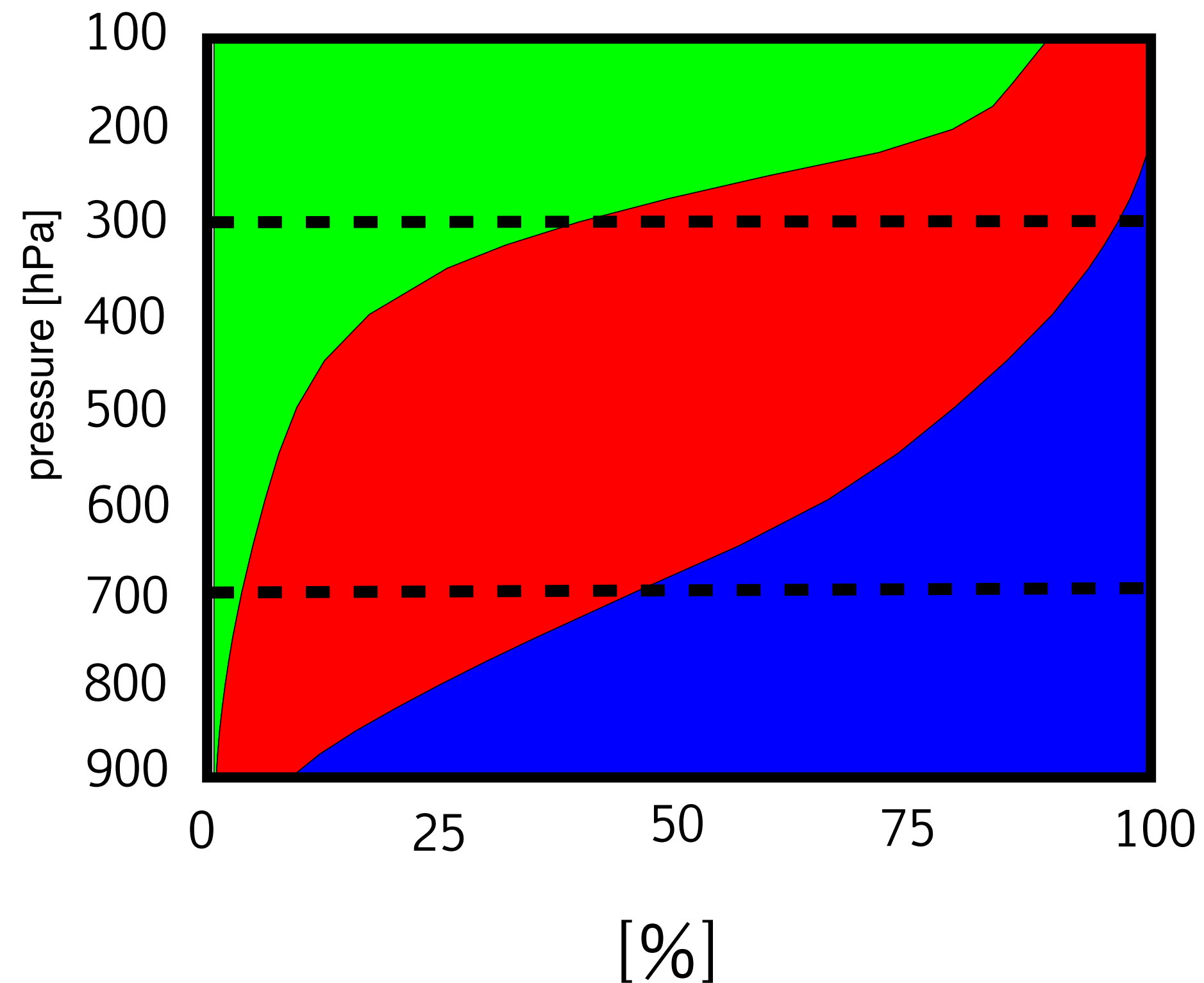
$$\overline{f}_{\text{ARC}}^{\text{ANN}}(p|\Omega_i)$$



The largest fractions ( $> 60\%$ ) of air between 300-700 mb last contact the PBL at **midlatitudes**.

# Annual Mean Arctic Air Mass Fraction

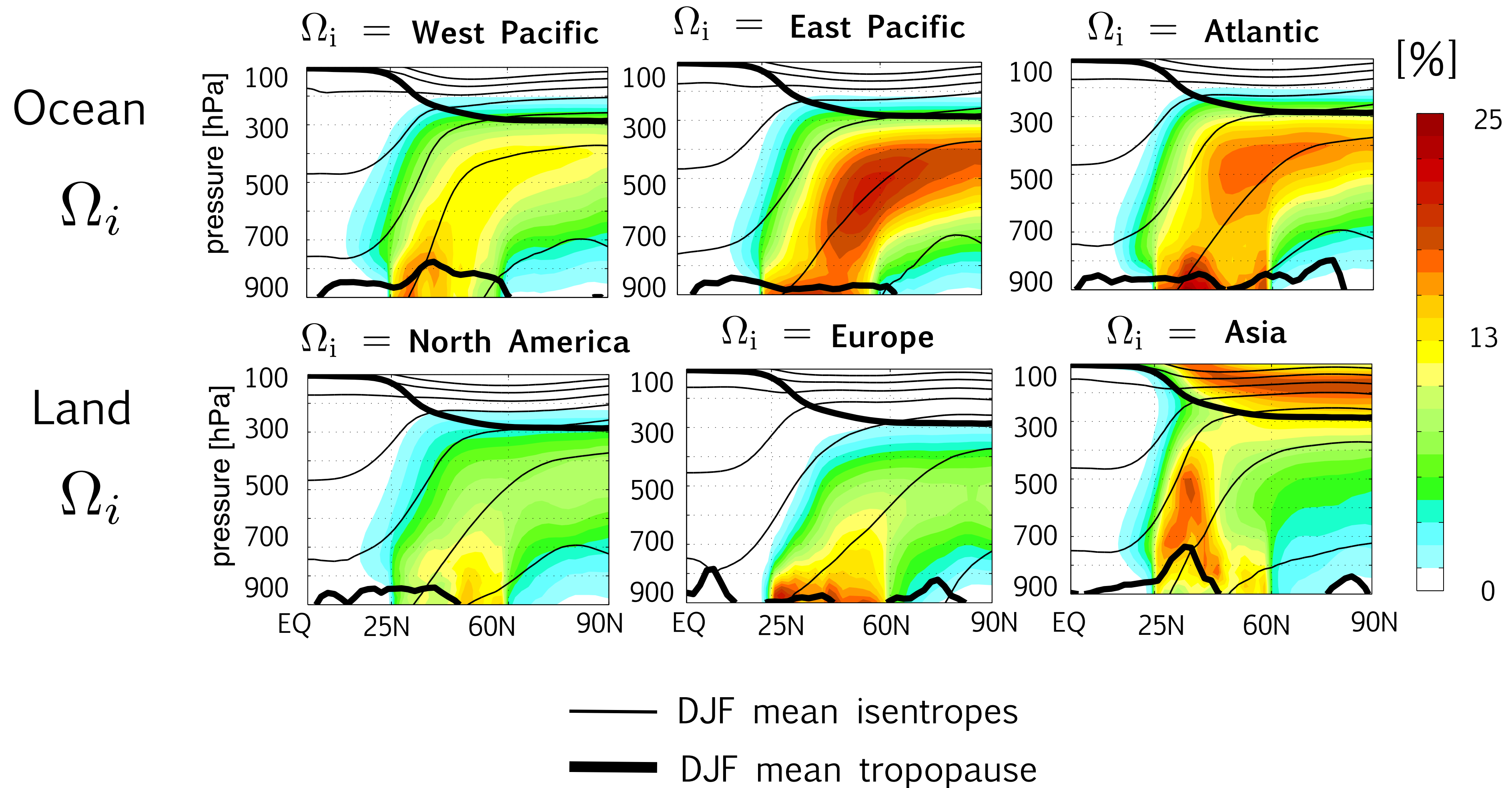
$$\overline{f}_{\text{ARC}}^{\text{ANN}}(p|\Omega_i)$$



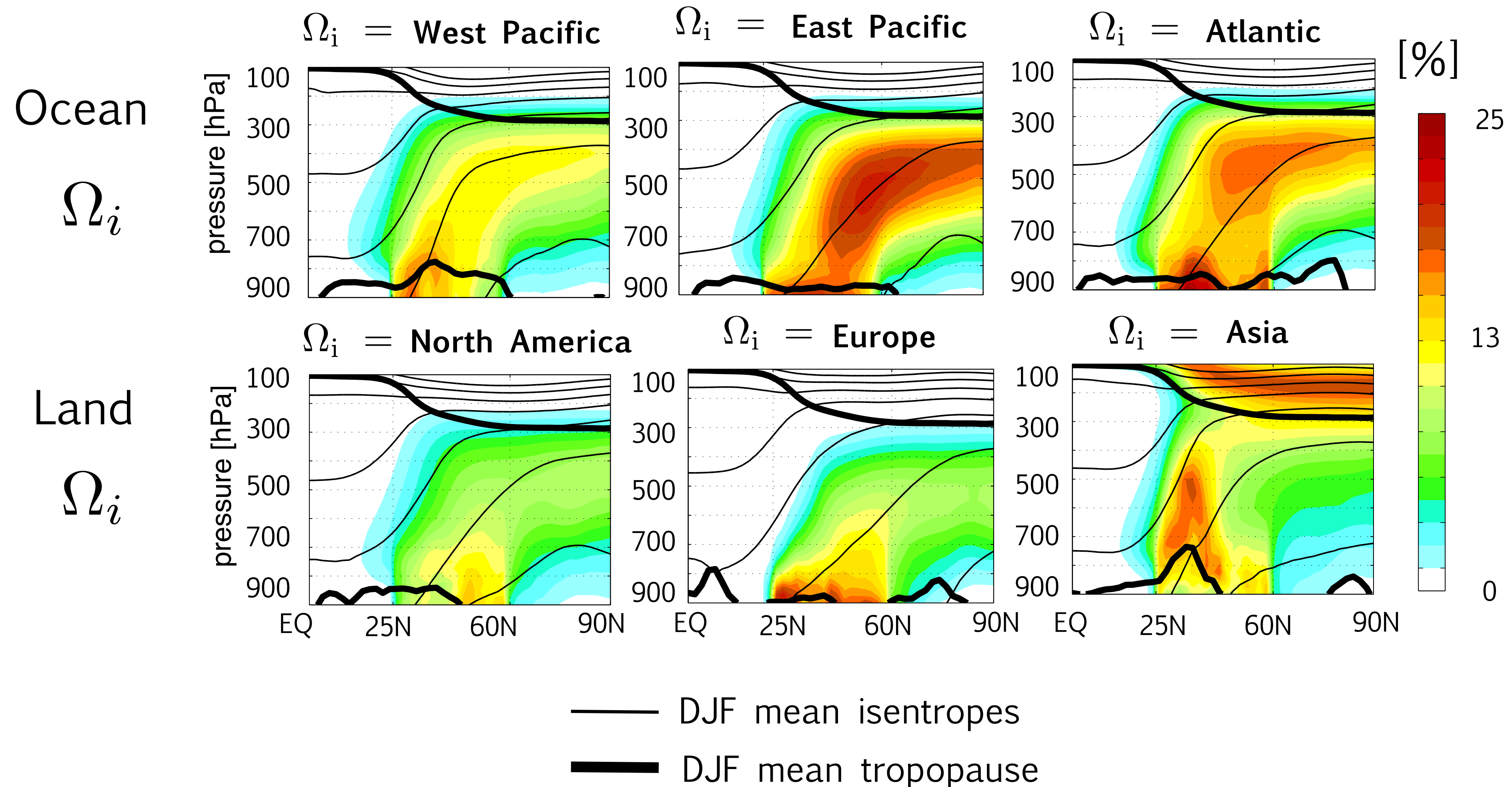
- There is ~10% less  $\Omega_{\text{MID}}$ -air in summer (JJA) compared to winter (DJF) (i.e. seasonal variations in the total amount of air are second order).

Biggest seasonal differences manifest in **where** air last contacts the PBL ...

DJF Air Mass Fraction  $\overline{f}^{\text{DJF}}(\mathbf{r}|\Omega_i)$  That Was Last over NH Midlatitudes

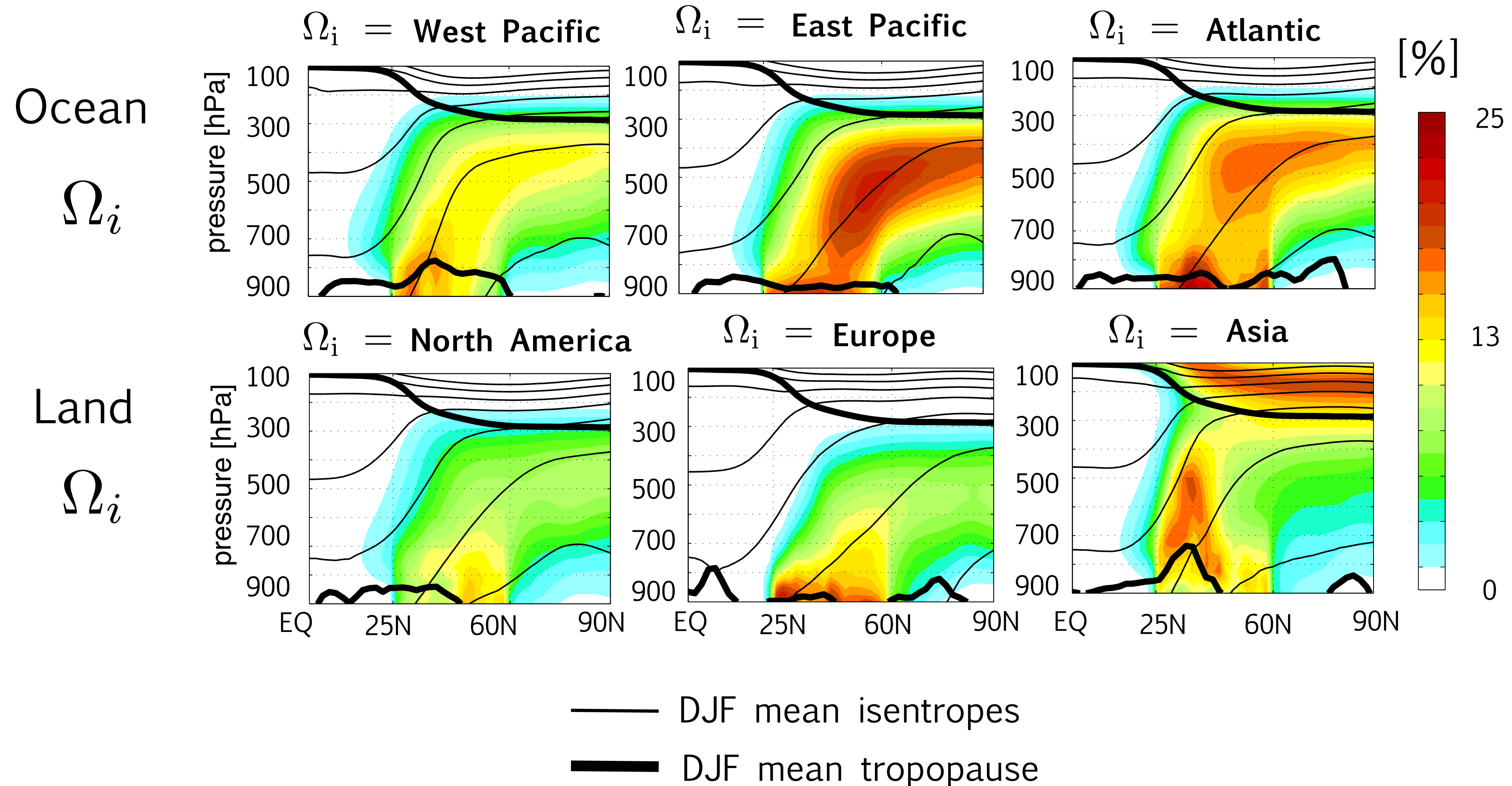


During winter the majority of Arctic air **last contacts midlatitudes over the oceans.**

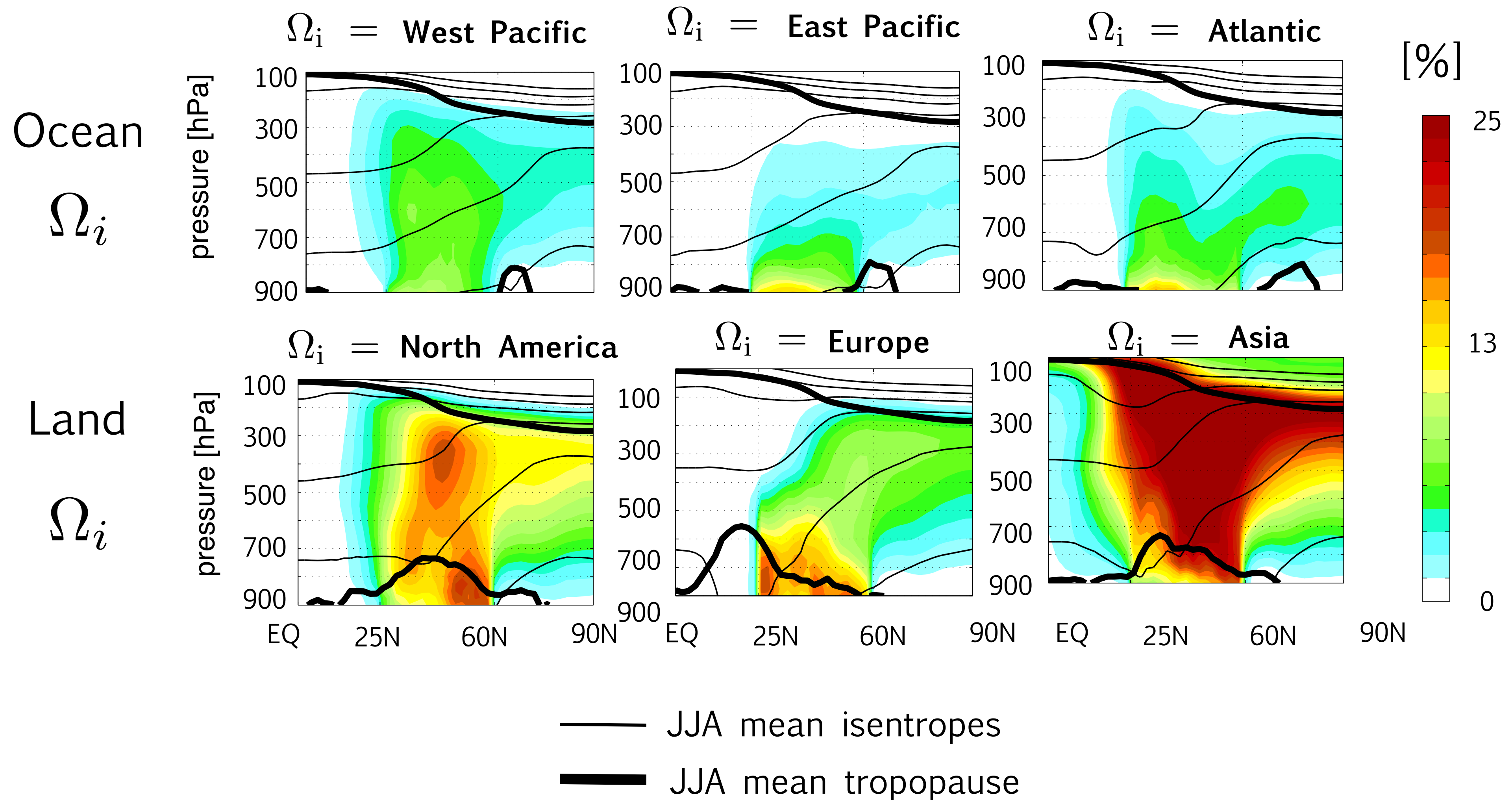




Nearly 30% of  $\Omega_{\text{MID}}$  -air originates over the East Pacific.

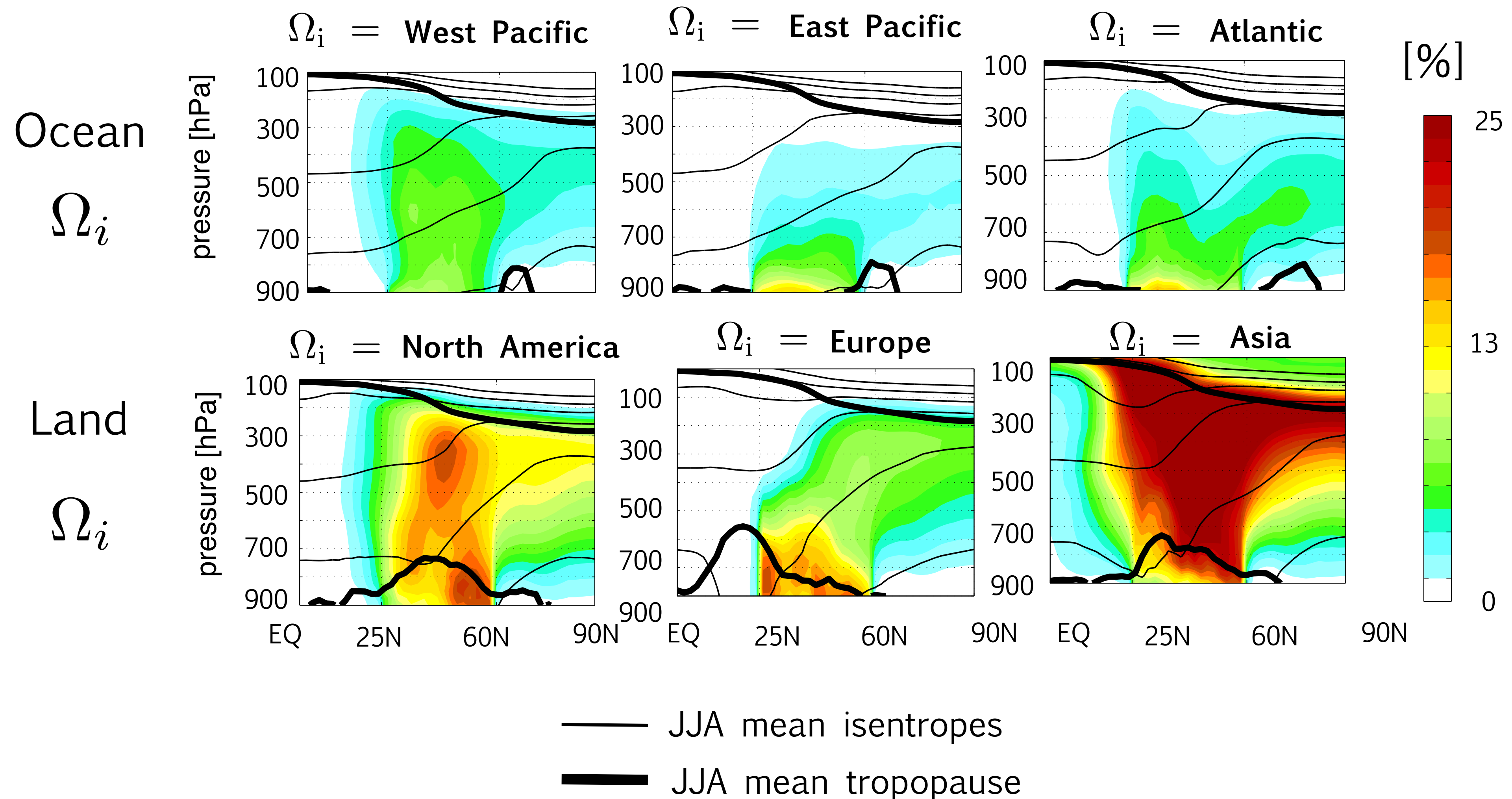


JJA Air Mass Fraction  $\bar{f}^{\text{JJA}}(\mathbf{r}|\Omega_i)$  That Was Last over NH Midlatitudes





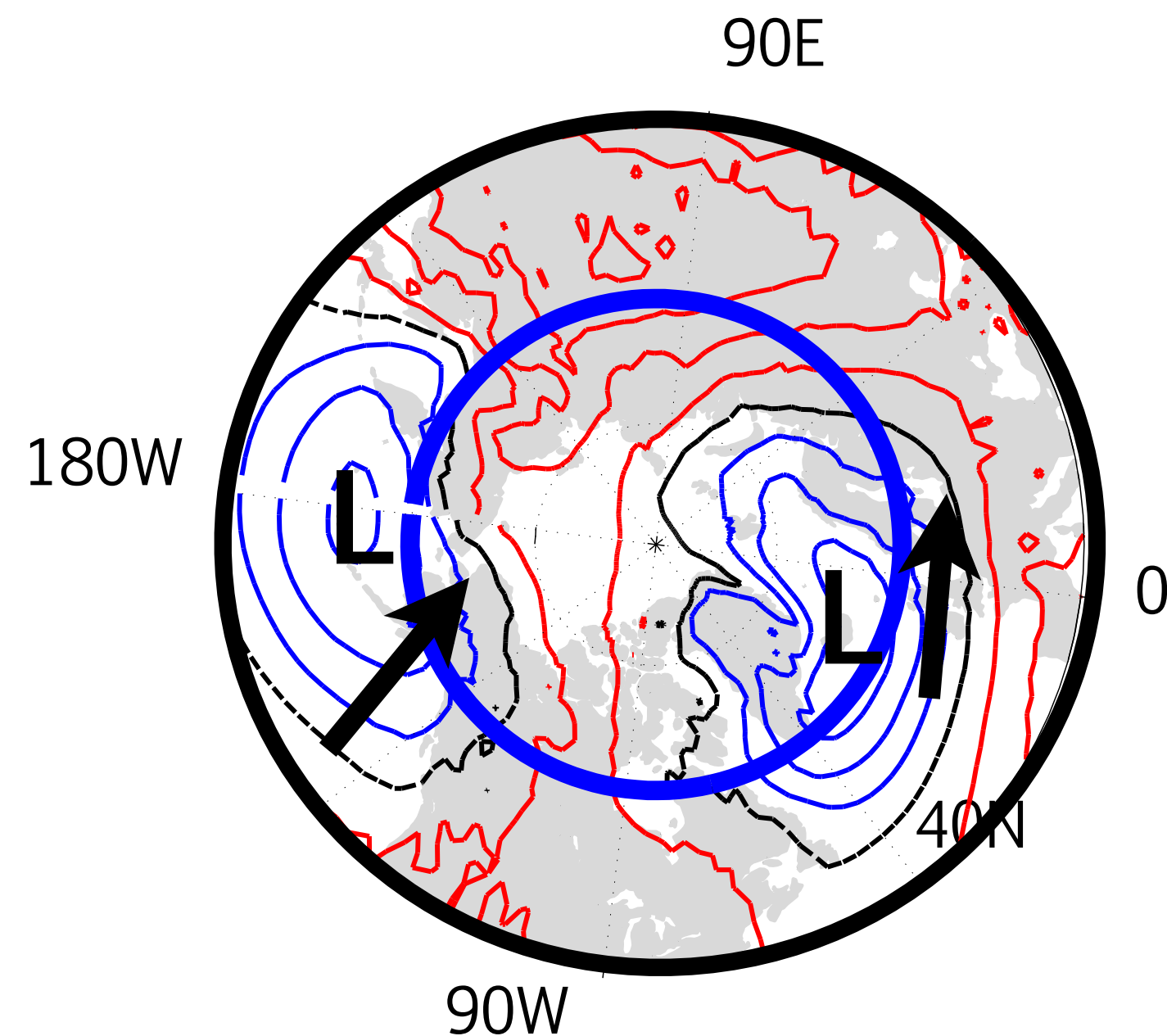
During summer the majority of Arctic air **last contacts**  
**midlatitudes over land**, largely over Asia (~40%).



(i) Seasonal variations in transport out of the boundary layer/lower troposphere control the (un) labeling of  $\Omega_i$  -air

- (i) Seasonal variations in transport out of the boundary layer/lower troposphere control the (un) labeling of  $\Omega_i$  -air

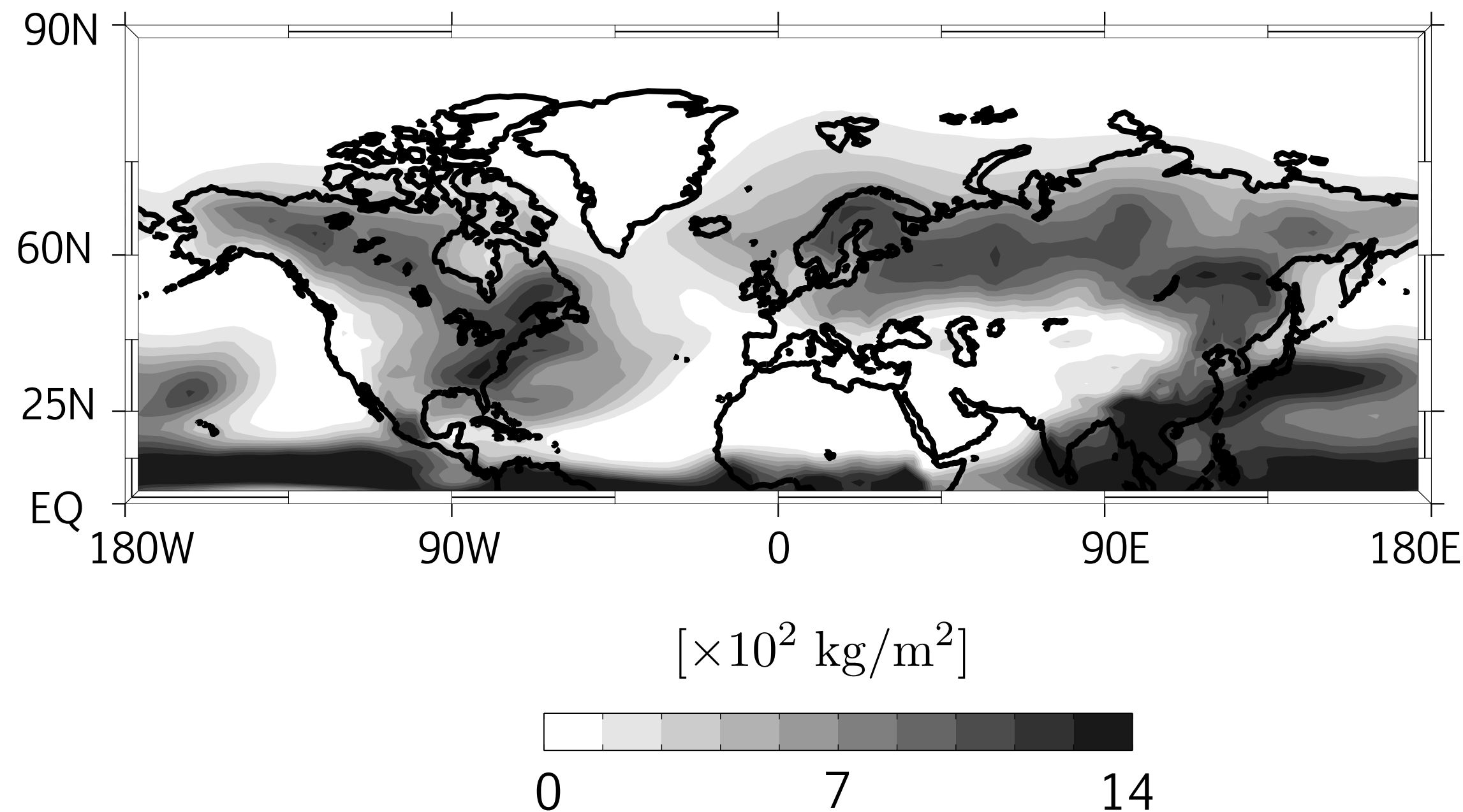
## DJF Sea Level Pressure



- During winter low level convergence and mean ascent associated with the Icelandic and Aleutian lows drive  $\Omega_{EPAC}$  - and  $\Omega_{ATL}$  - air away from the PBL.

- (i) Seasonal variations in transport out of the boundary layer/lower troposphere control the (un) labeling of  $\Omega_i$ -air

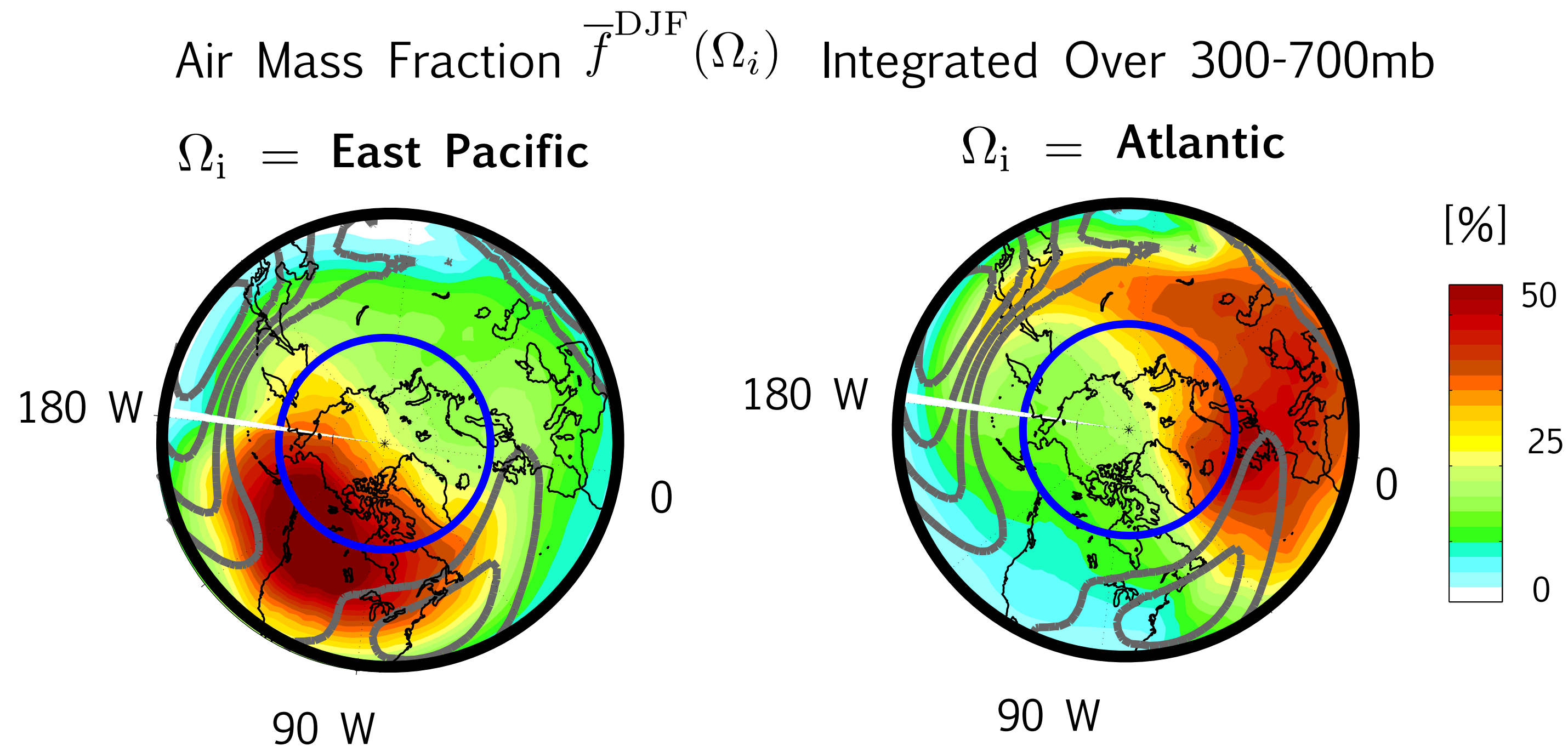
### JJA Convective Cloud Fraction (300-900 mb column)



- During summer, convection over land drives  $\Omega_{\text{ASI}}$  - and  $\Omega_{\text{NAM}}$ -air away from the boundary layer, reducing its likelihood of being relabeled over midlatitudes.

- (ii) Seasonal variations in the midlatitude tropospheric jet modulate the poleward transport of  $\Omega_i$  -air into the middle and upper Arctic.

- (ii) Seasonal variations in the midlatitude tropospheric jet modulate the poleward transport of  $\Omega_i$  -air into the middle and upper Arctic.

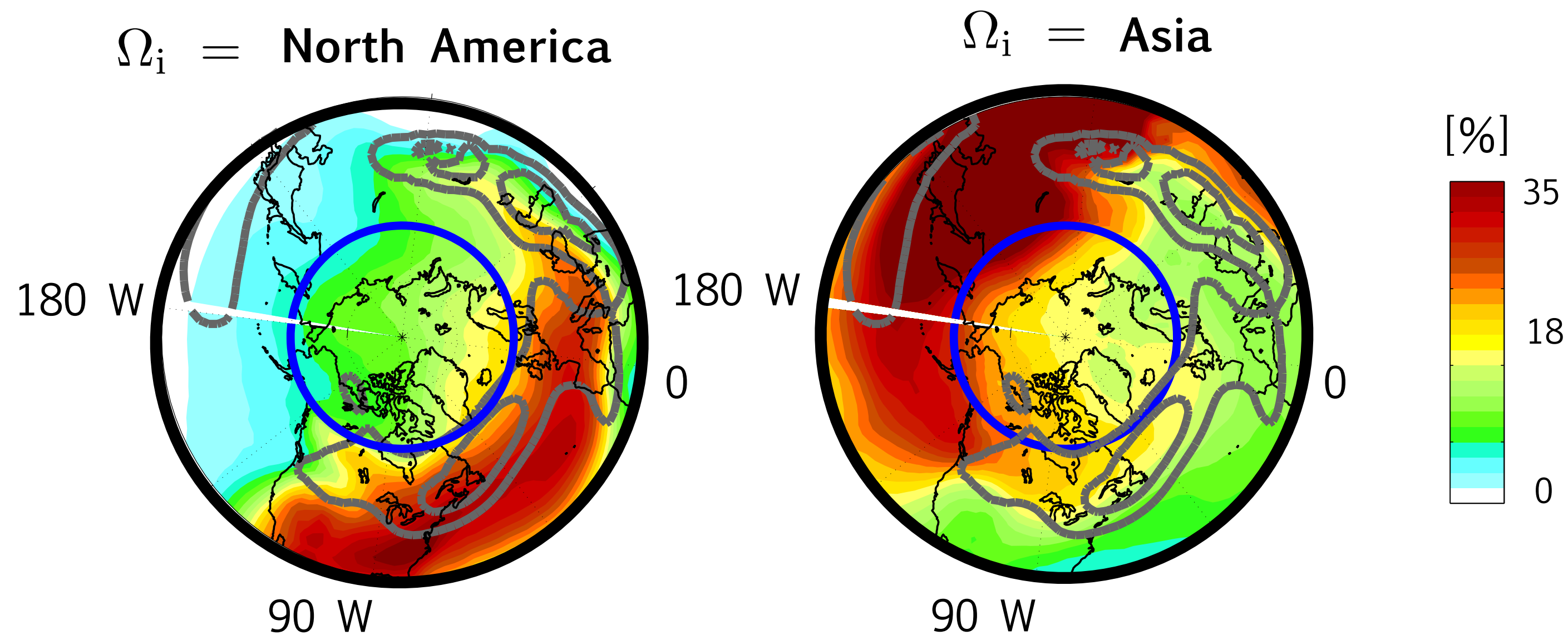


During winter, along-isentropic transport peaks at the exit regions of the midlatitude storm tracks (grey contours) over the Pacific and Atlantic basins (i.e. outflow regions within warm conveyor belts) [e.g. *Echkardt and Stohl (2004)*].



- (ii) Seasonal variations in the midlatitude tropospheric jet modulate the poleward transport of  $\Omega_i$ -air into the middle and upper Arctic.

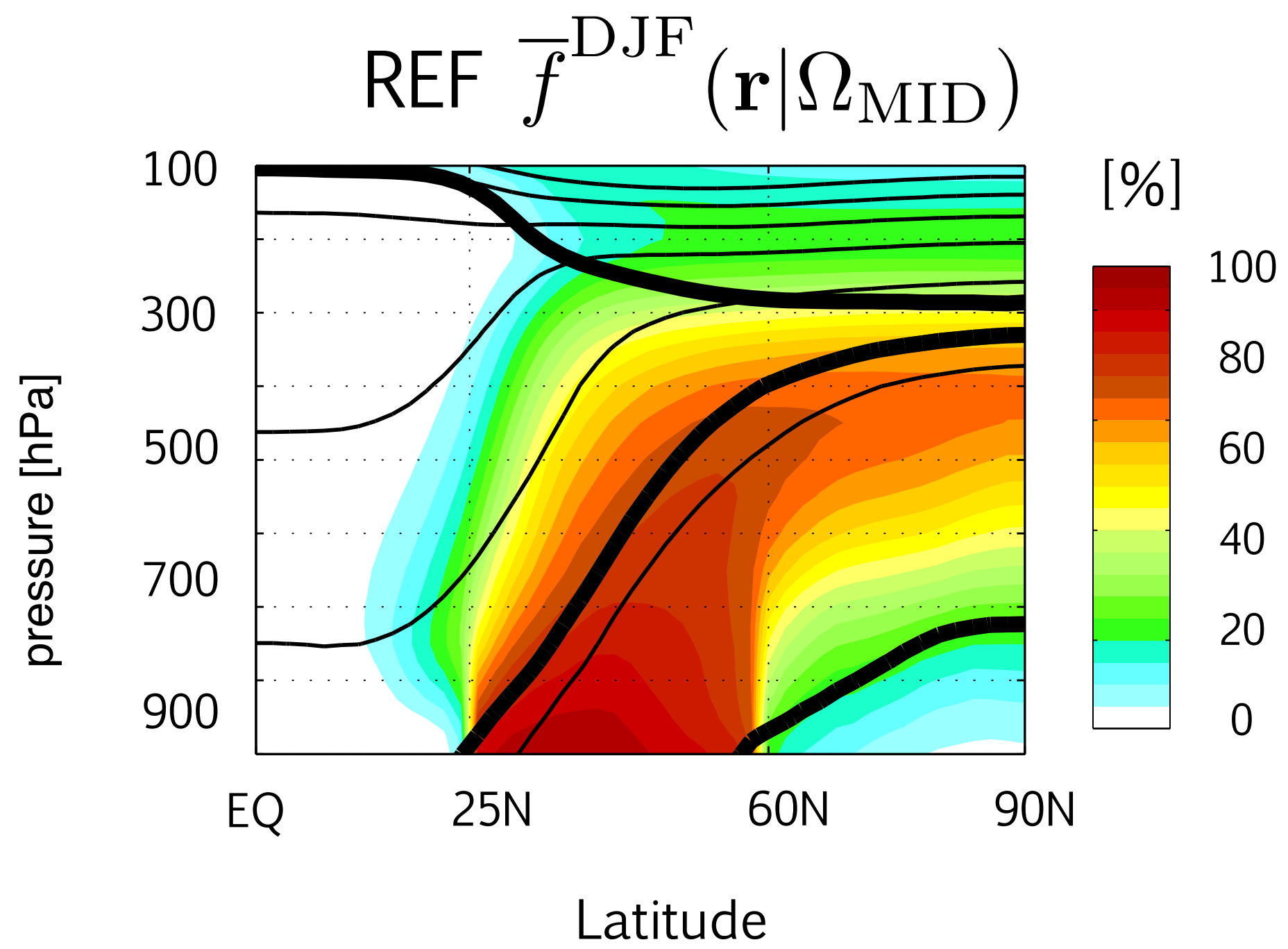
Air Mass Fraction  $\overline{f}^{\text{JJA}}(\Omega_i)$  Integrated Over 300-700mb



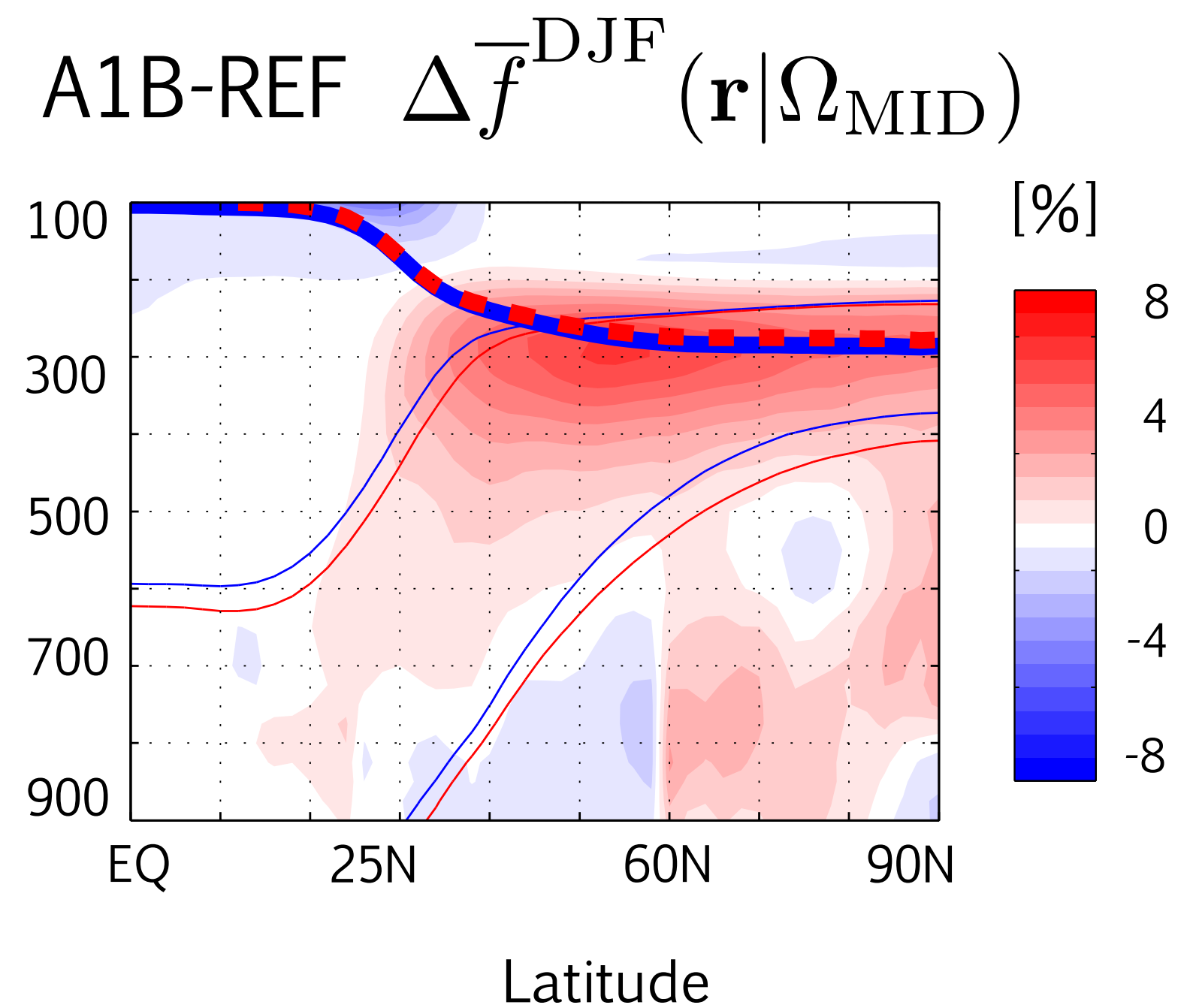
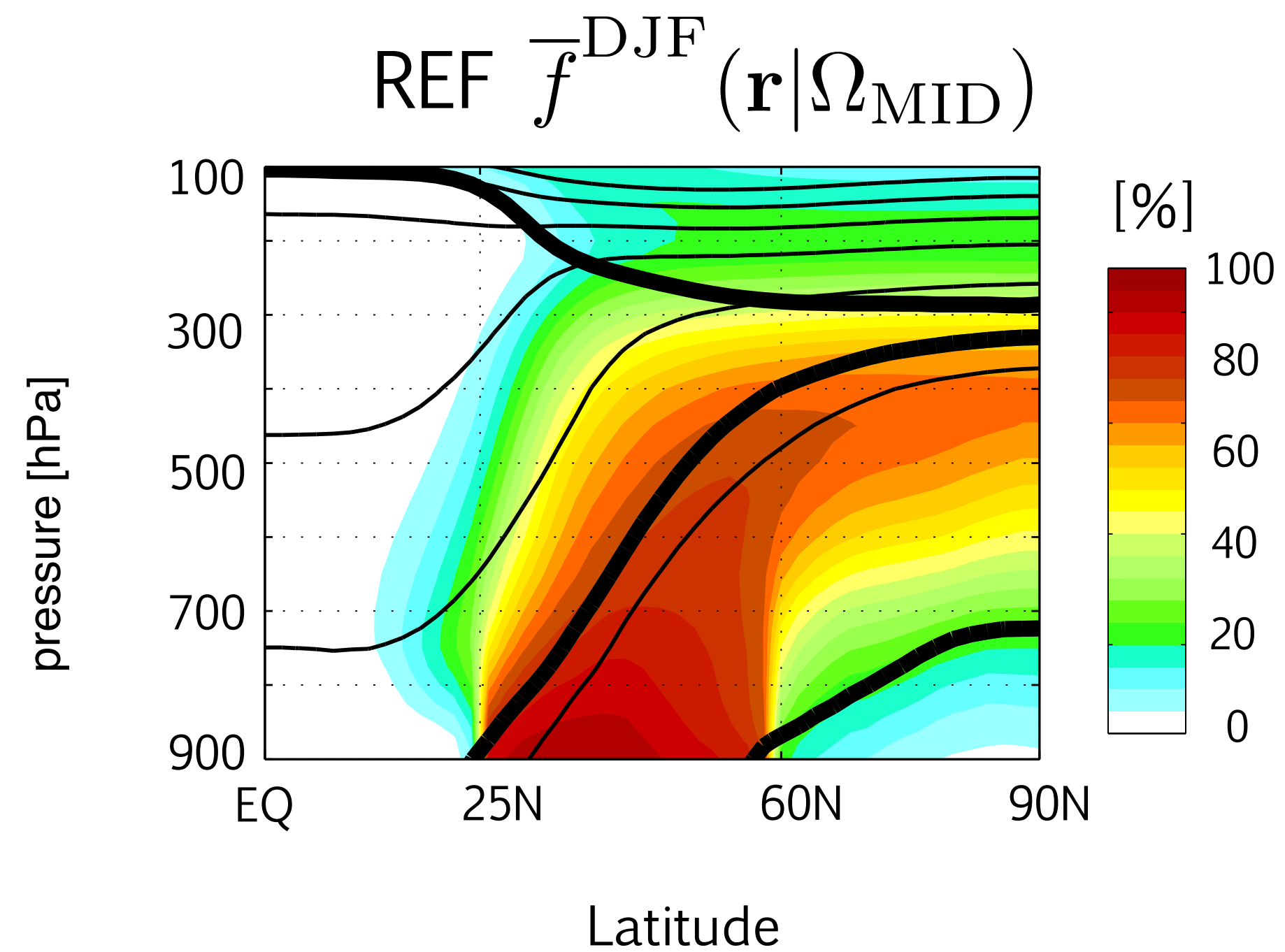
During summer, the NH jet is overall weaker and peaks over the Atlantic. Correspondingly,  $\Omega_{\text{NAM}}$ -air is dragged over the Atlantic, where it is relabeled at the boundary layer. By comparison,  $\Omega_{\text{ASI}}$ -air enters the Arctic directly over Siberia.

How does transport into the Arctic change in response to A1B warming?

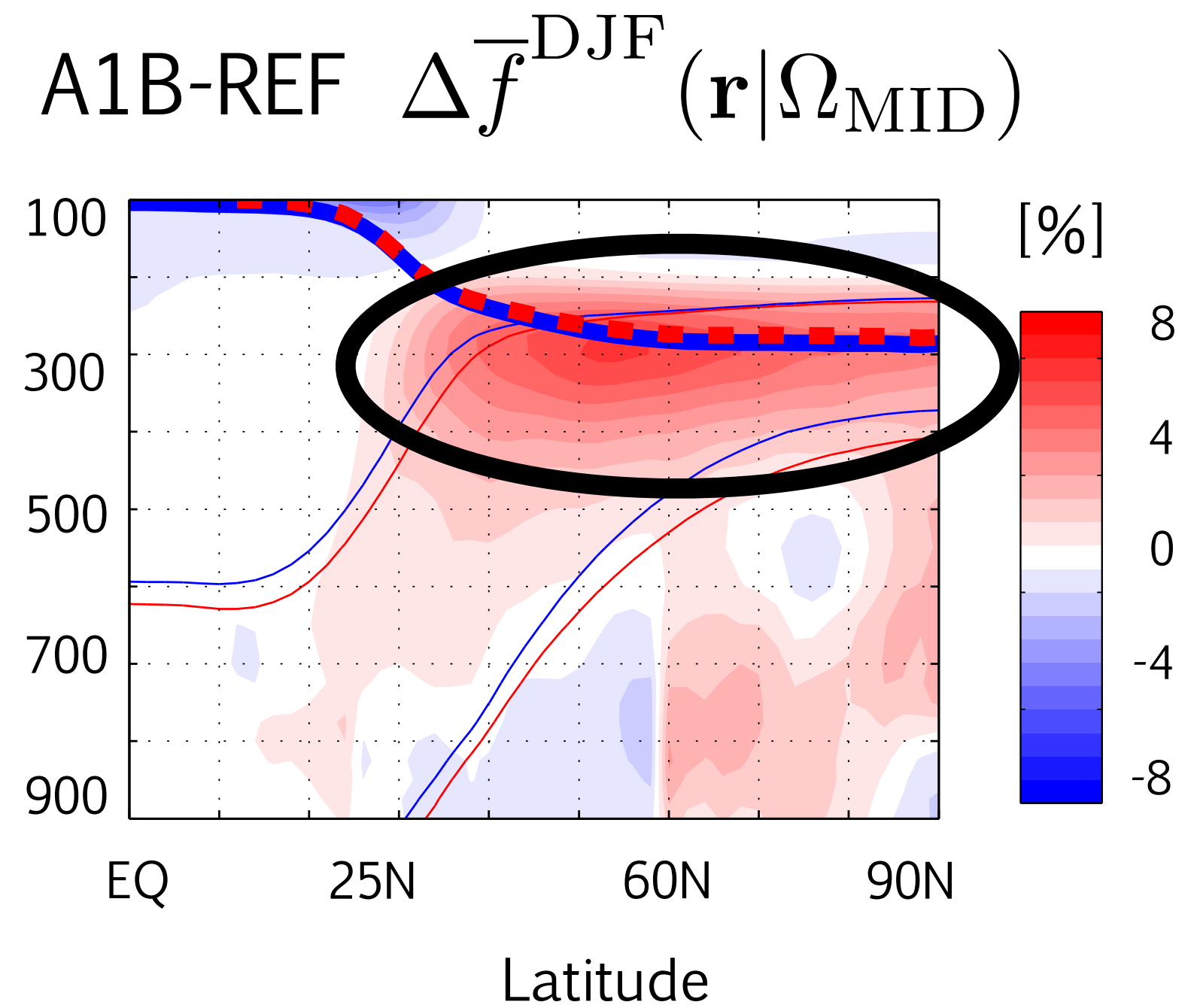
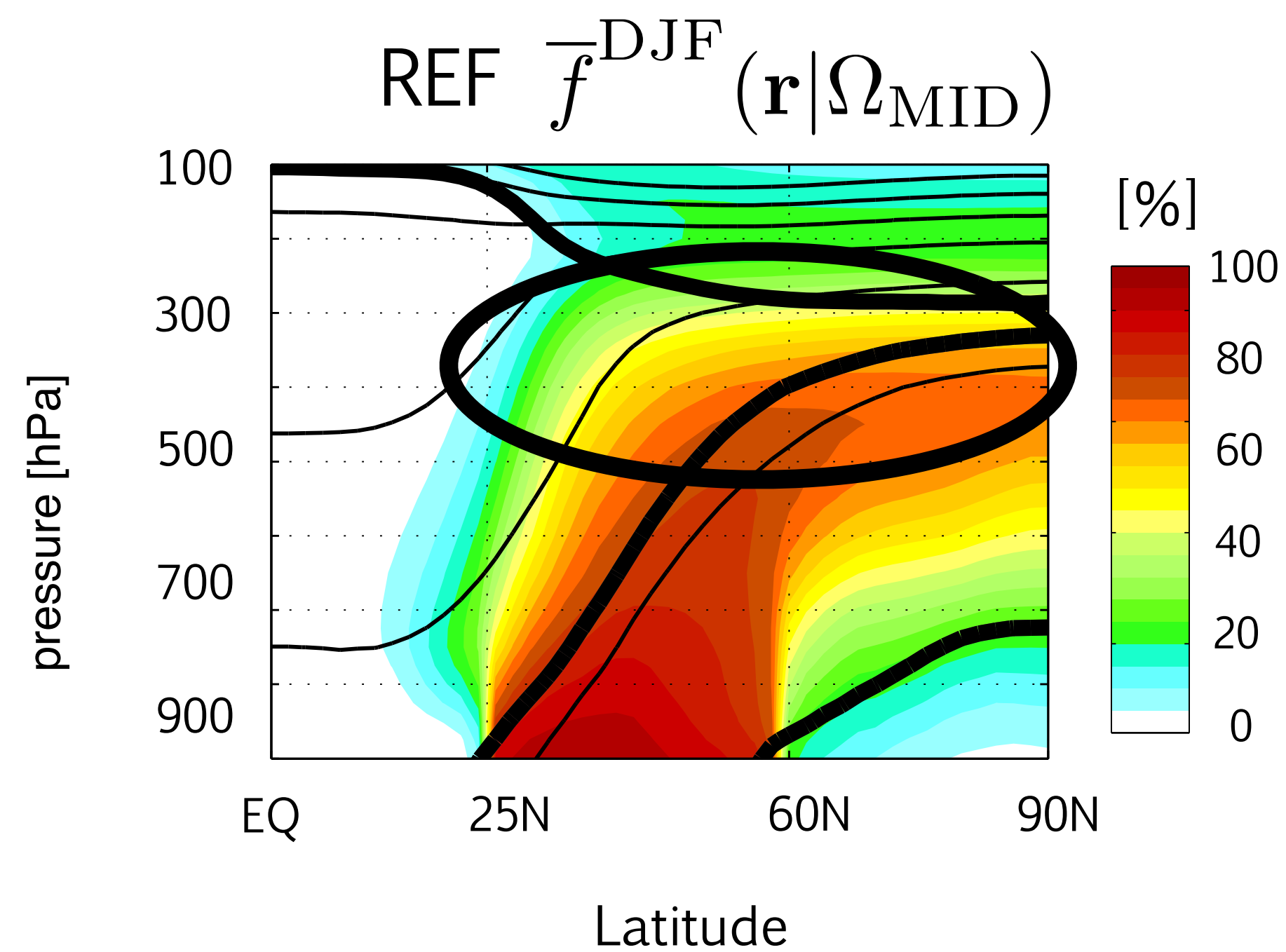




The winter transport response to A1B warming reveals **~10% increased fractions of midlatitude air** in the middle and upper Arctic troposphere.

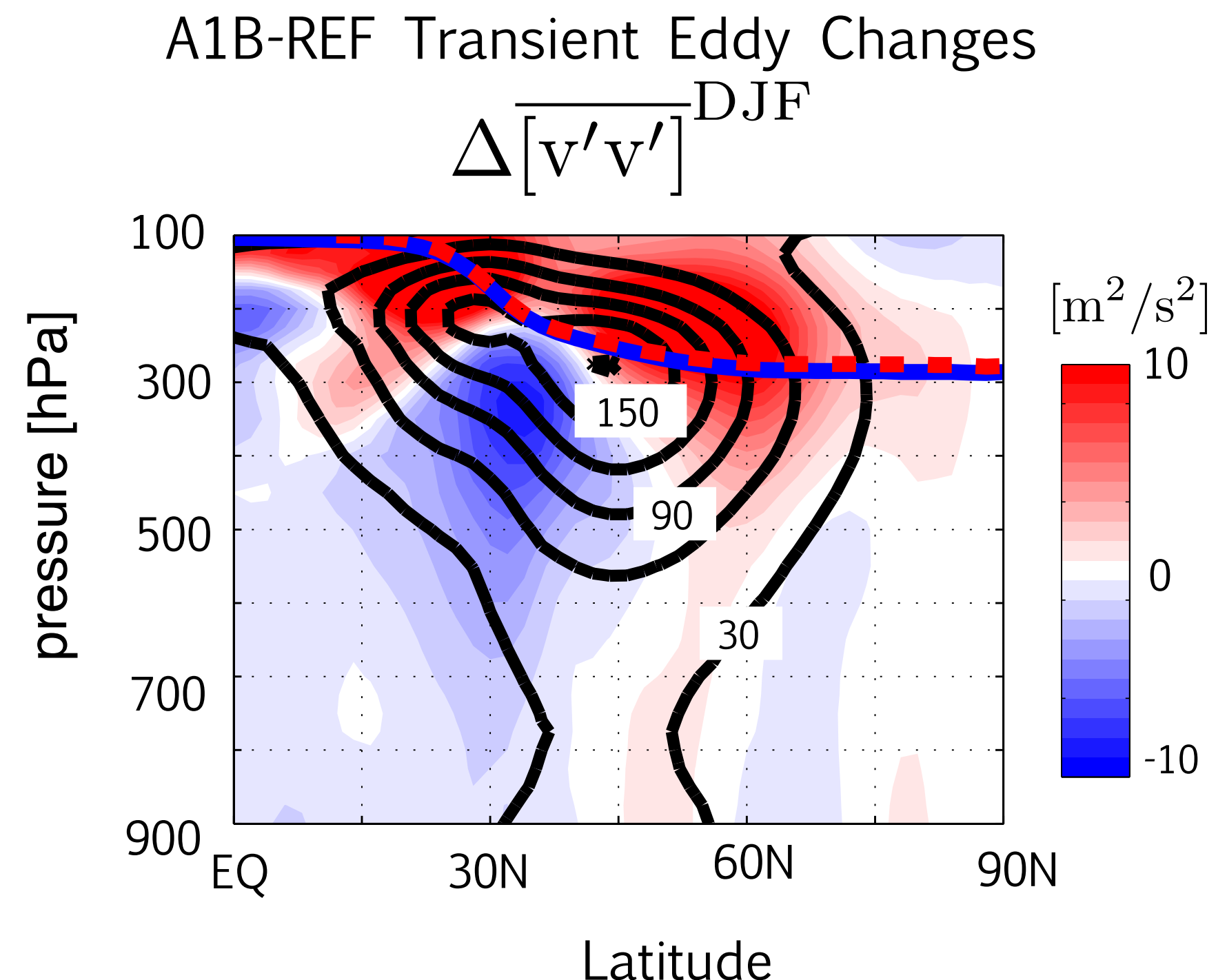
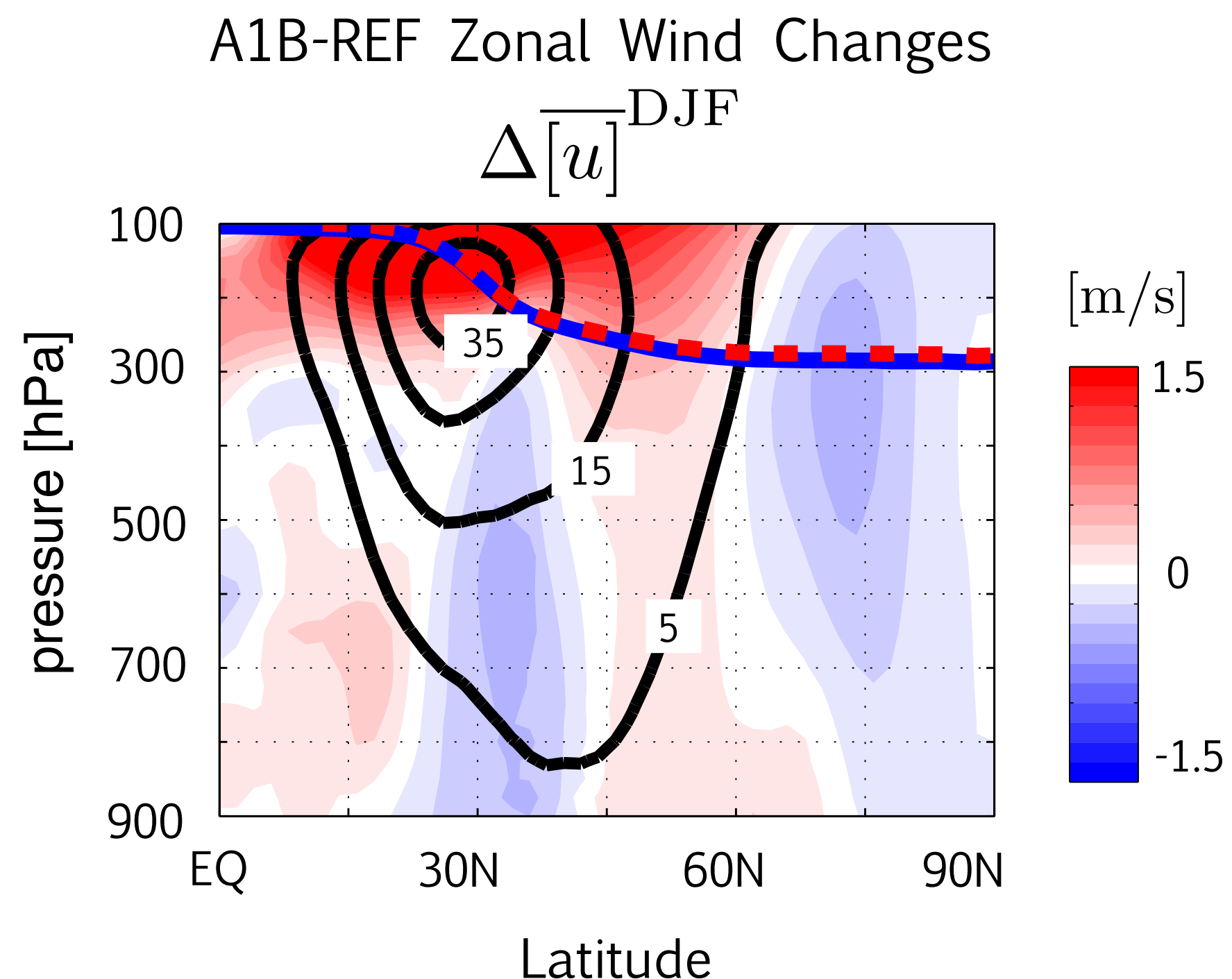


The largest response is in the upper troposphere ( $> 500$  mb) and reflects an upward shift in the climatology.



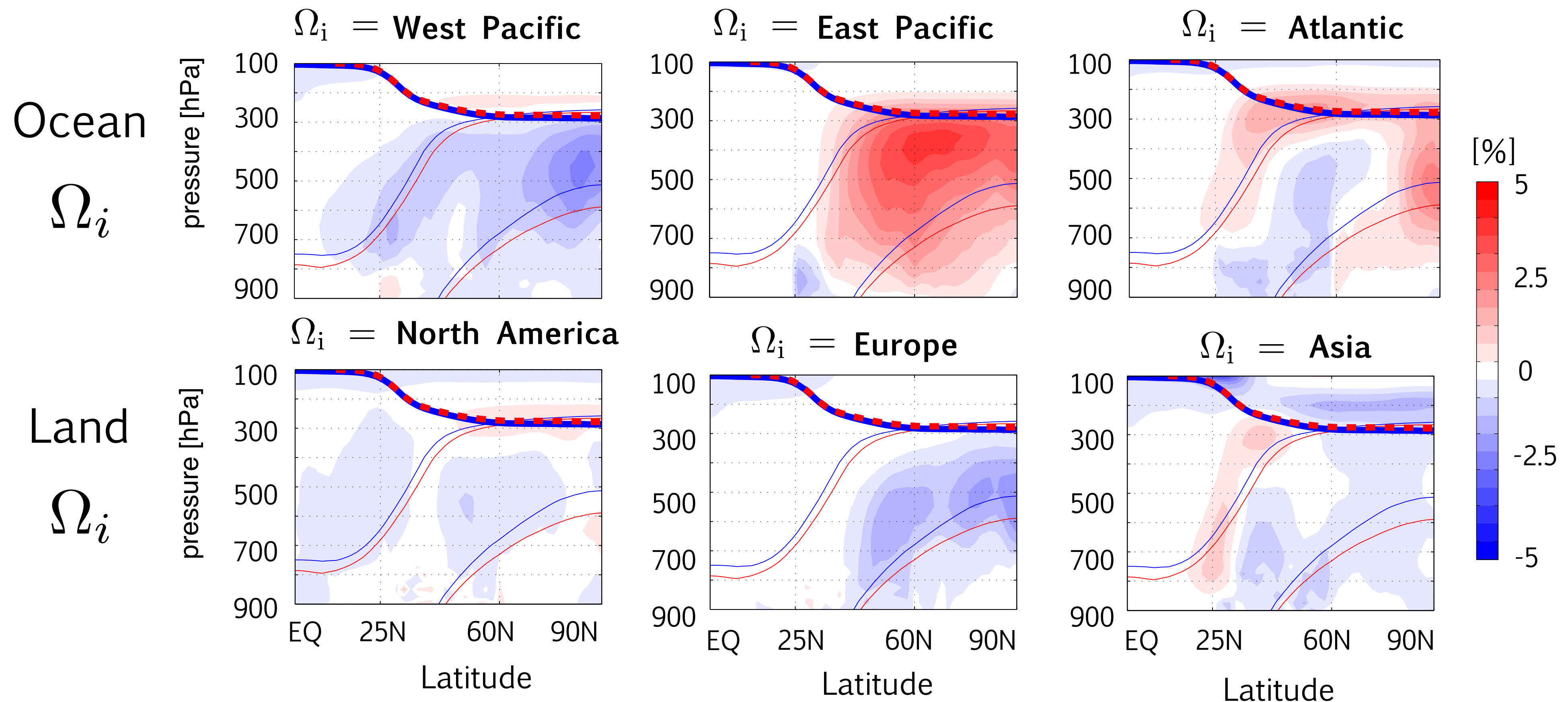
Increased middle and upper tropospheric (5-10%) fractions of  $\Omega_{\text{MID}}$ -air are consistent with **multi-model mean dynamical responses** among the CMIP3/5 models:

- upward shifted zonal winds (e.g. *Yin et al. (2005)*, *Fyfe and Saeko (2006)*)
- upward intensification of the transient eddy meridional velocity (*Wu et al. (2010)*)



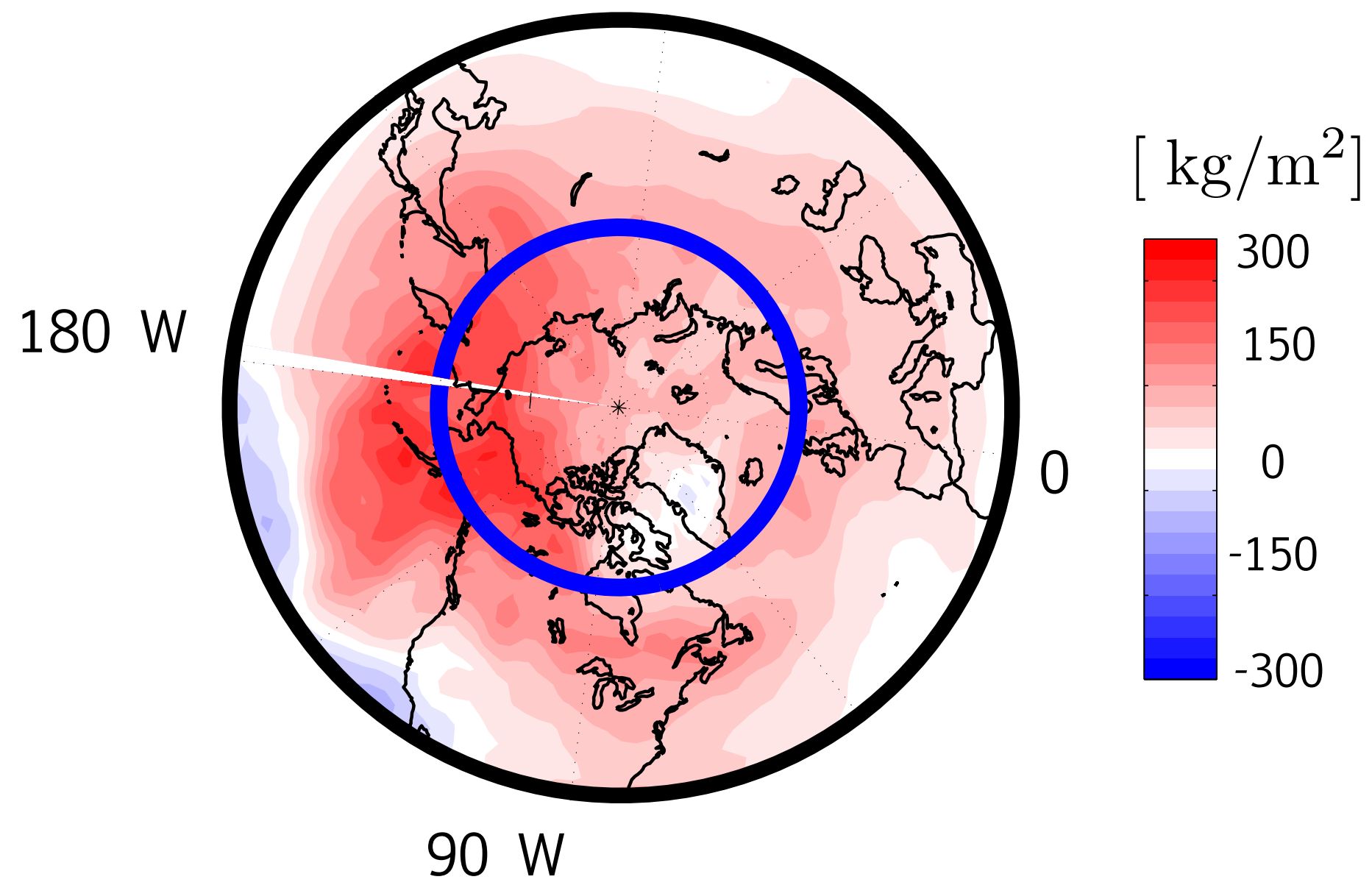
Enhanced midlatitude air in future winters stems largely from **more PBL contact over the East Pacific** (i.e. “fresher” Arctic).

A1B-REF  $\Delta \bar{f}^{\text{DJF}}(\mathbf{r}|\Omega_i)$  for Midlatitude Origin Regions



$$\Delta \bar{f}^{\text{DJF}}(\Omega_{\text{EPAC}})$$

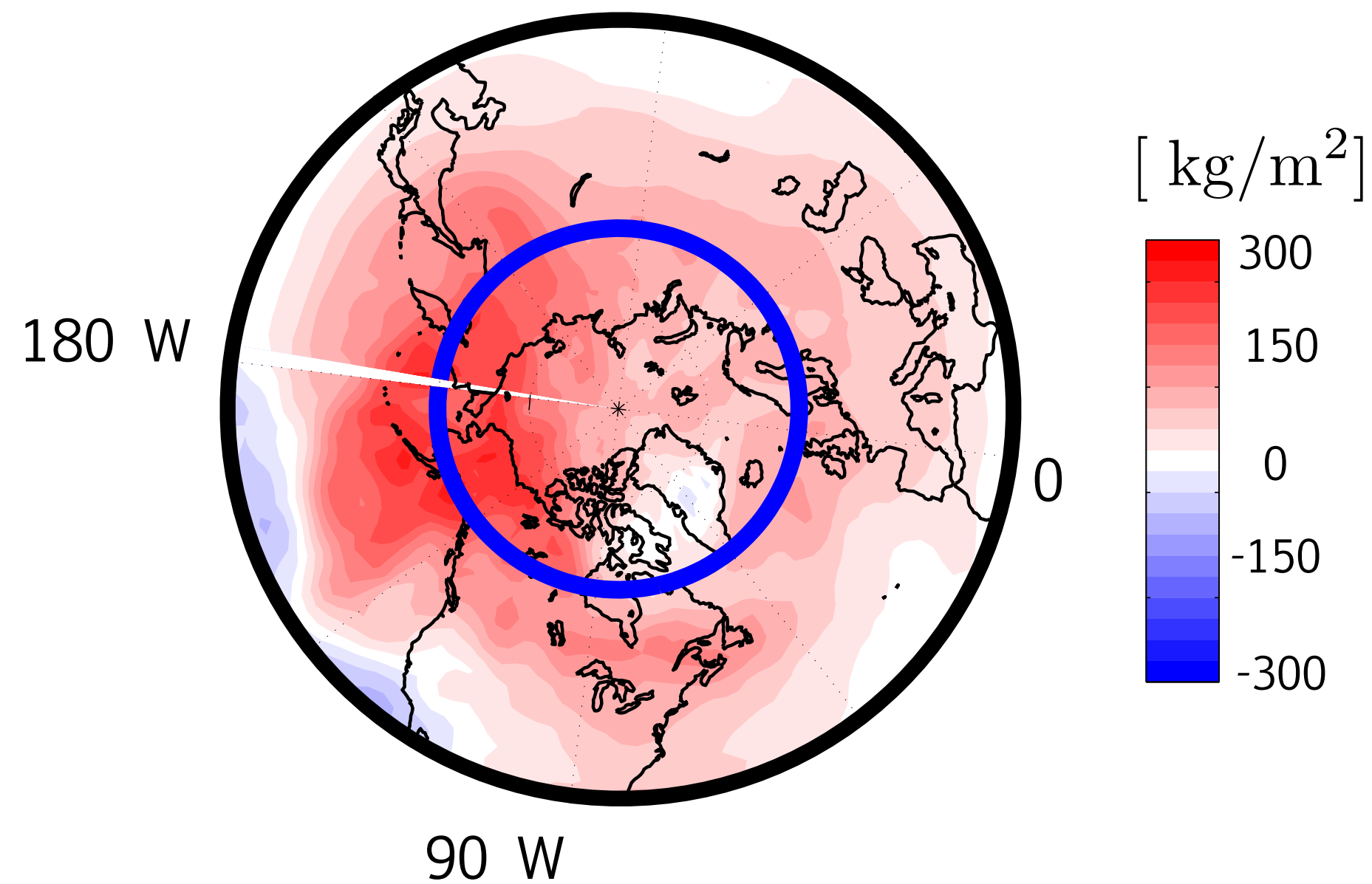
(500-900 mb column)



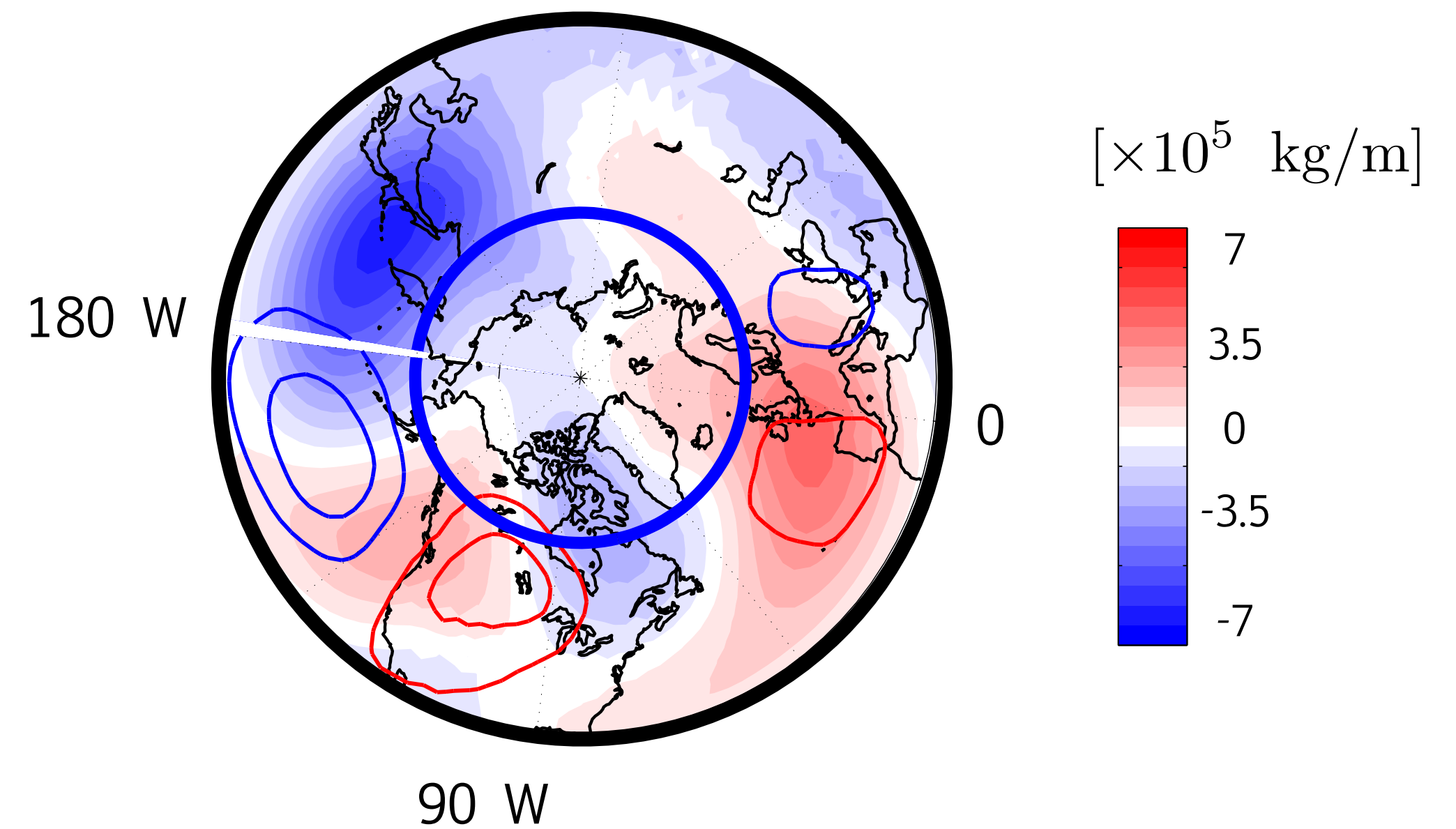


The changes  $\Delta \overline{f}^{\text{DJF}}(\Omega_{\text{EPAC}})$  are consistent with a barotropic cyclonic anomaly over the west coast of North America (i.e. intensified poleward flow) (*Simpson et al. (2014), Park and An (2014)*)

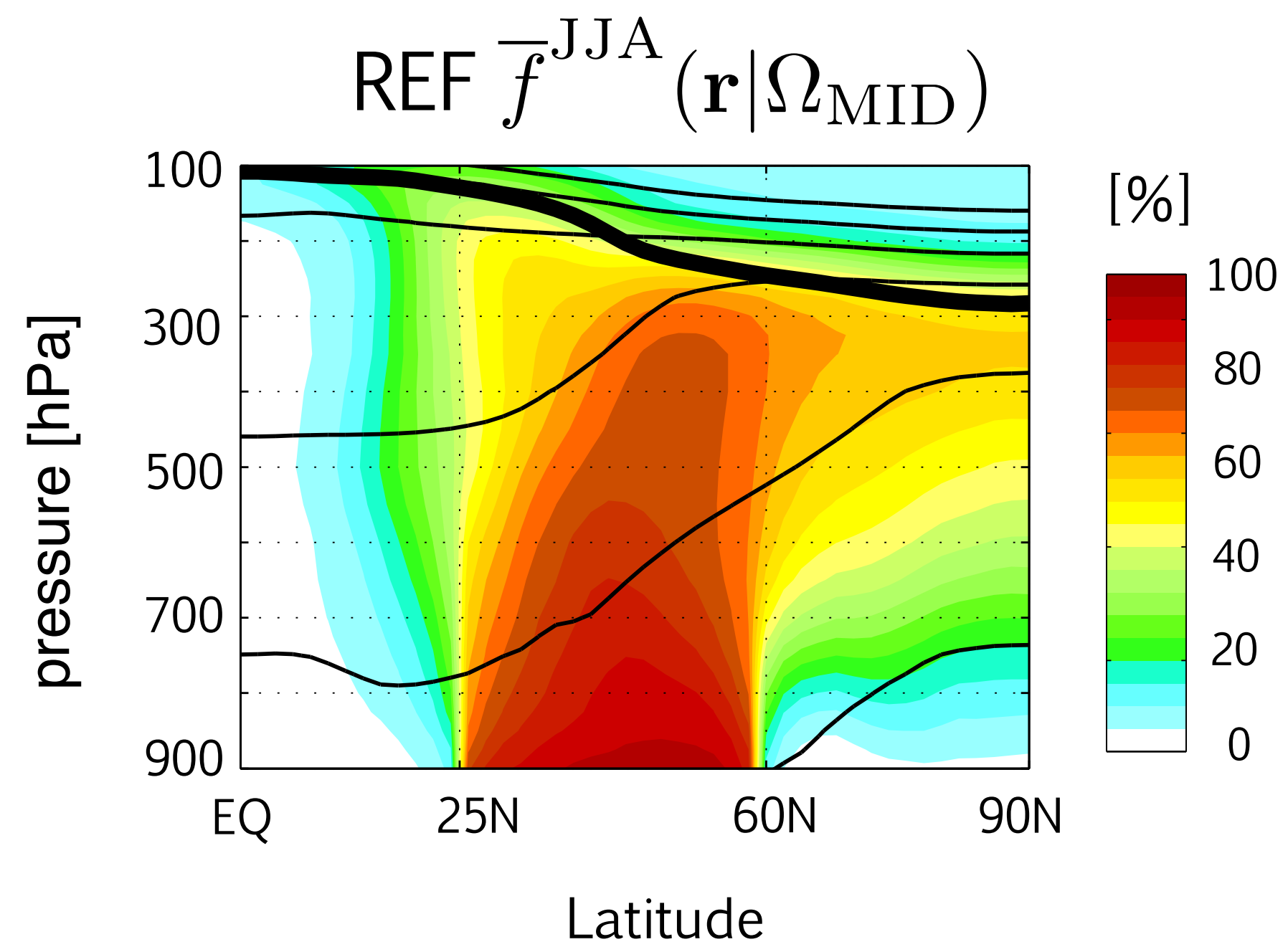
$\Delta \overline{f}^{\text{DJF}}(\Omega_{\text{EPAC}})$   
(500-900 mb column)



$\Delta \overline{\Phi}^{*\text{DJF}}$   
(500-900 mb column)

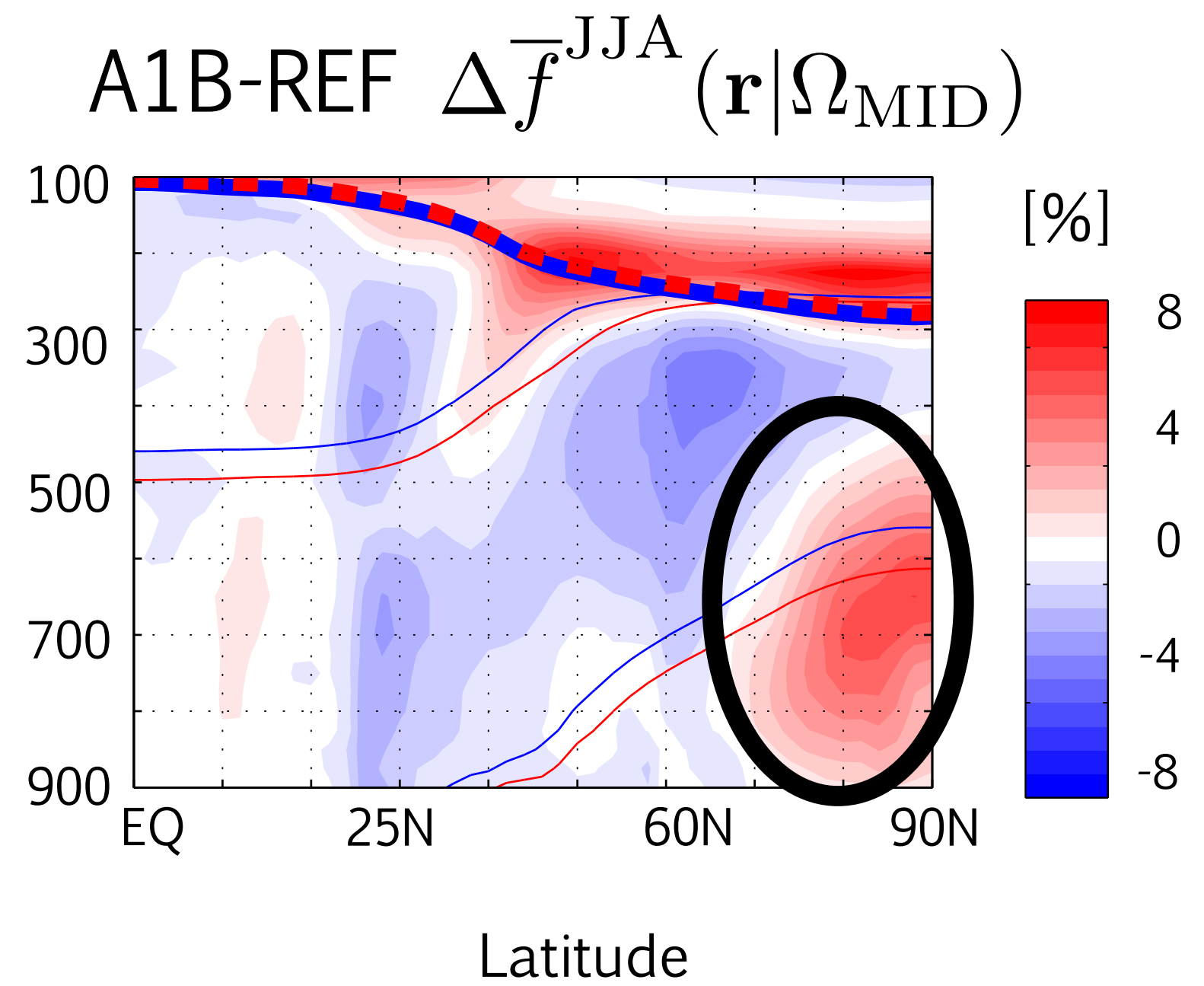
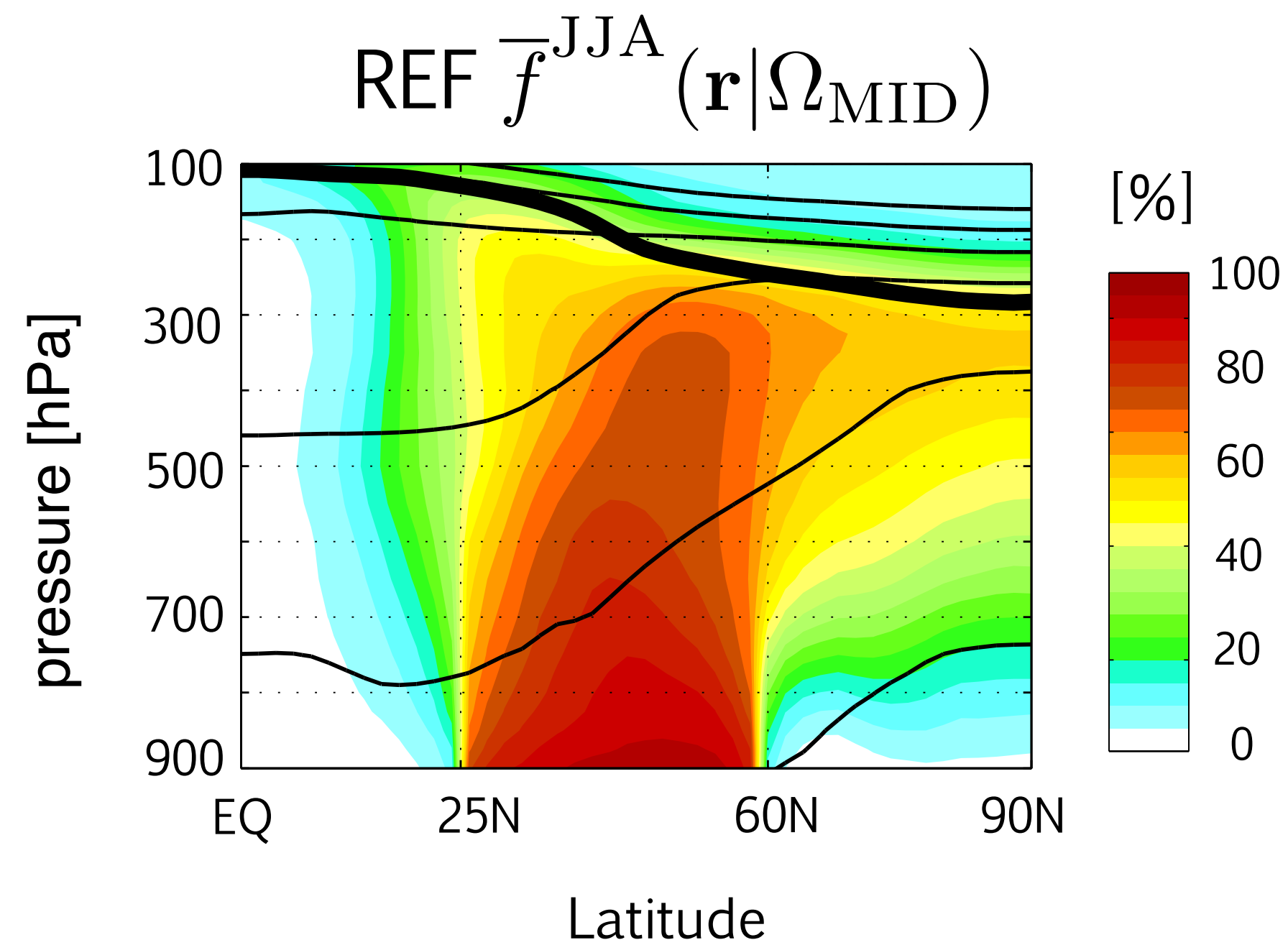


What is the NH summer response in air mass origin?



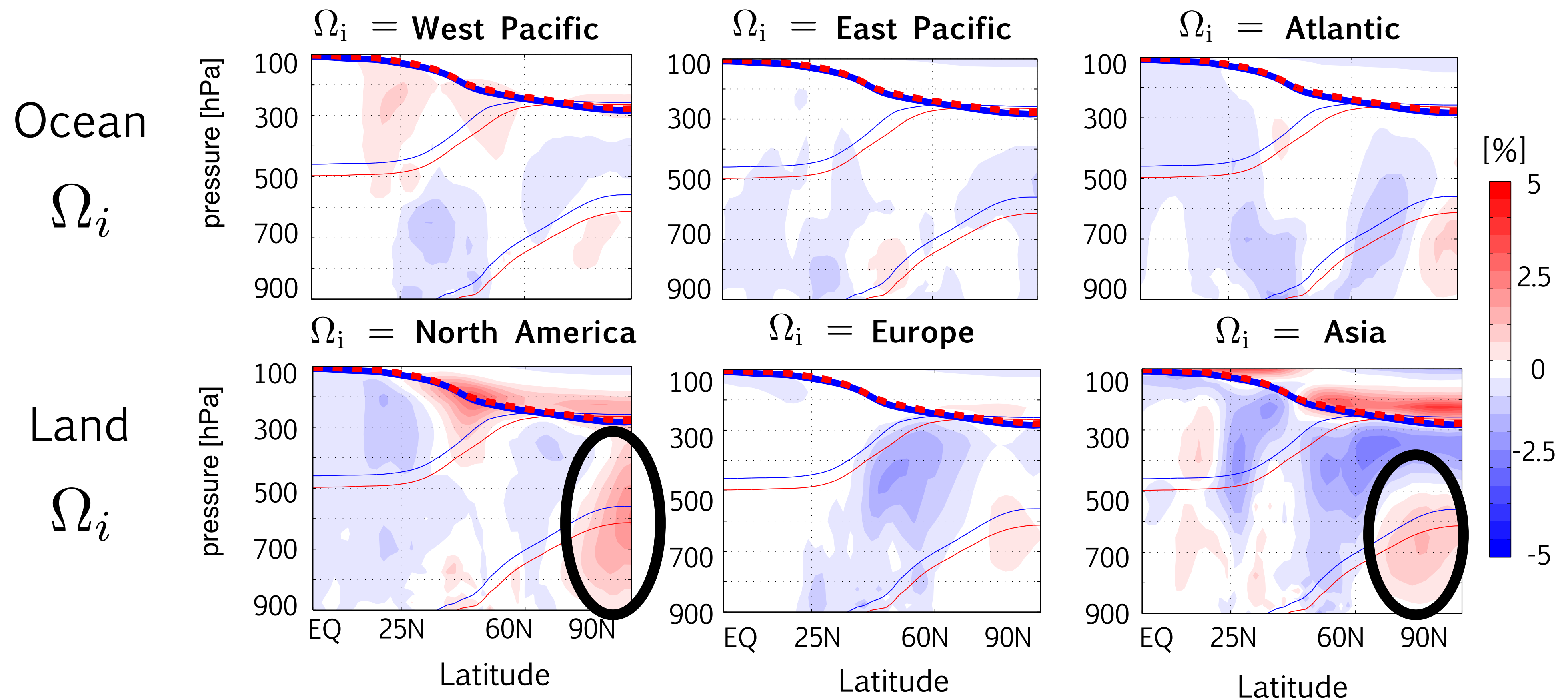


The transport response to A1B warming in summer reveals **~10% increased fractions of midlatitude air in the middle and lower Arctic troposphere.**



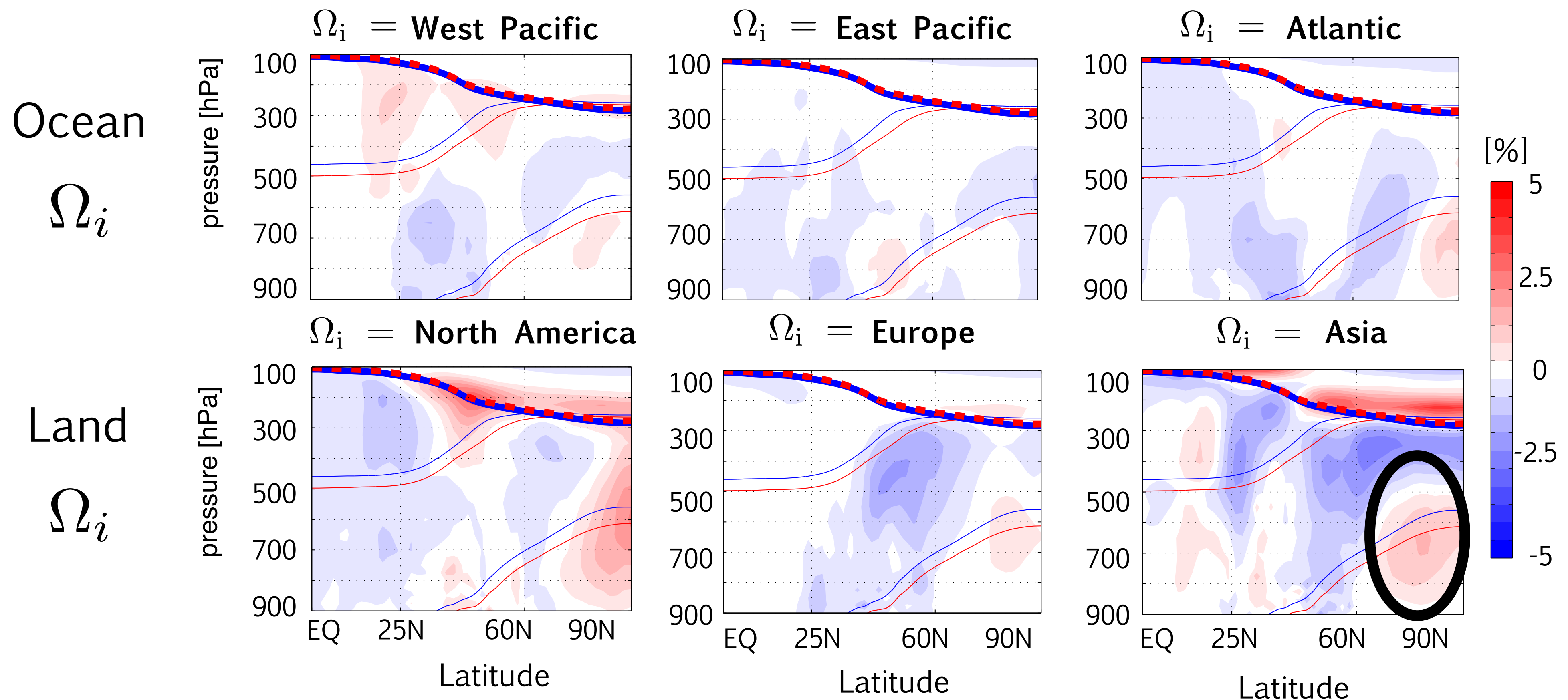
Increases in midlatitude air in future summers stem from **enhanced contact over North America and Asia**.

A1B-REF  $\Delta \bar{f}^{\text{JJA}}(\mathbf{r}|\Omega_i)$  for Midlatitude Origin Regions



Increases Arctic fractions  $\Delta \bar{f}^{\text{JJA}}(\Omega_{\text{ASI}})$  are worrisome in light of increased black carbon emissions from South Asia [Koch and Hansen (2005)].

## Zonal Mean $\Delta \bar{f}^{\text{JJA}}(\mathbf{r}|\Omega_i)$ for Midlatitude Origin Regions



# Conclusions

Transport uncertainties affect models' representations of species that are important for understanding current and future Arctic climate.

# Conclusions

Transport uncertainties affect models' representations of species that are important for understanding current and future Arctic climate.

The air mass fraction disentangles the role of transport from chemistry and emissions and reflects the integrated (advective+diffusive) circulation.

# Conclusions

A climatology of air mass origin from GEOSCCM reveals that the majority (> 60%) of Arctic air above 700 mb originates at midlatitudes, largely over **oceans** during winter and over **land** in summer.

Response to A1B warming reveals **~10% more air of midlatitude origin**, stemming mainly from the East Pacific in winter

- “fresher” winters

# Conclusions

A climatology of air mass origin from GEOSCCM reveals that the majority (> 60%) of Arctic air above 700 mb originates at midlatitudes, largely over **oceans** during winter and over **land** in summer.

Response to A1B warming reveals **~10% more air of midlatitude origin**, stemming mainly from the East Pacific in winter and Asia in summer.

- “fresher” winters
- “dirtier” summers

**Implication:** Emissions from Asia may need to be cut still more in light of *transport changes*.

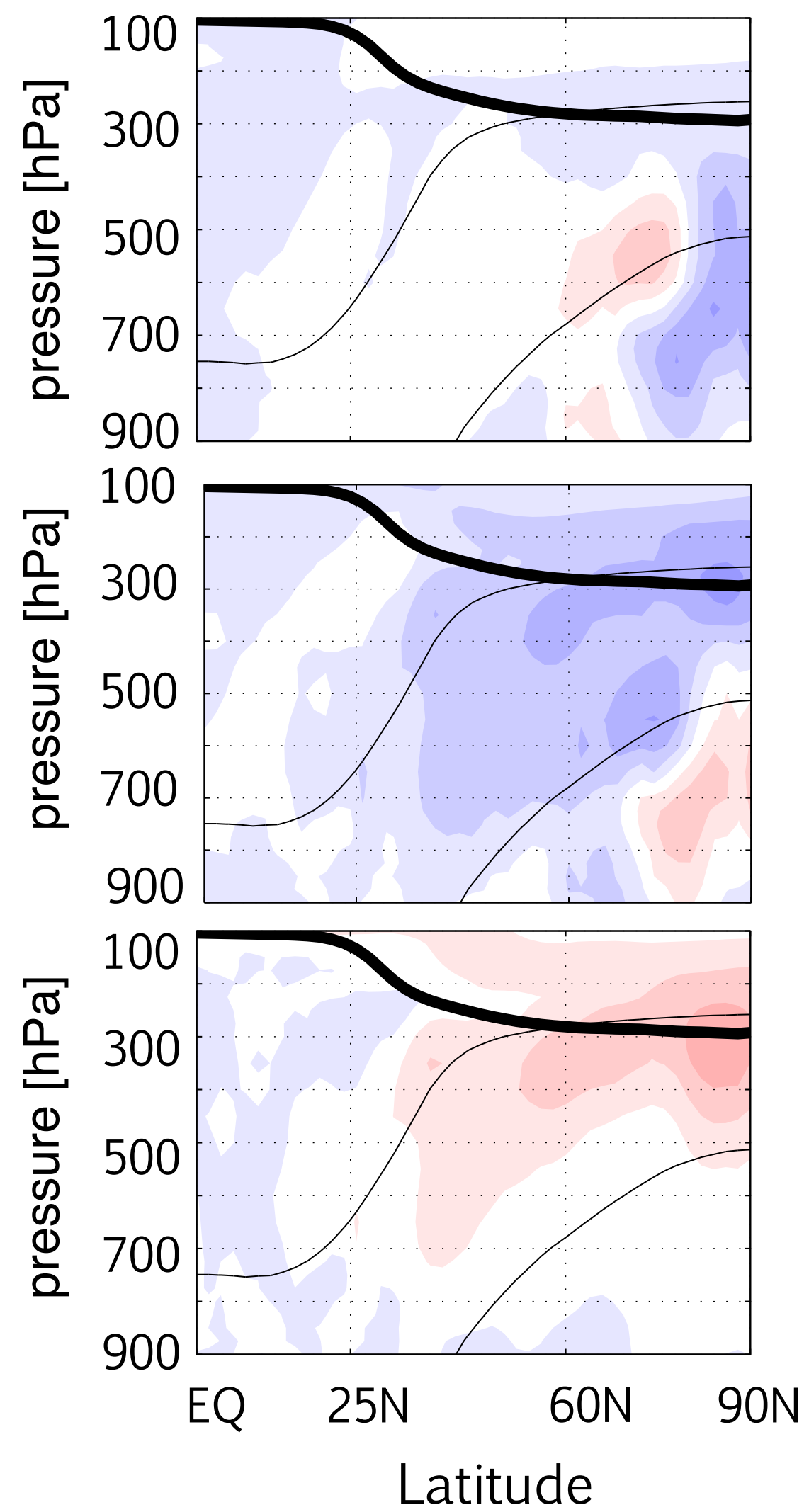


# Conclusions

Changes in air mass origin are largely interpretable in terms of CMIP5 multi-model projected changes in the **midlatitude tropospheric jet**.

**General Message:** The distributions of chemical species reflect interactions between transport, chemistry, and emissions. In order to understand current and future trace species' distributions we need to have a **rigorous grasp of the underlying transport**.

**(a)** REF DJF Internal  
Variability  $\delta \bar{f}^{\text{DJF}}(\mathbf{r}|\Omega_i)$



**(b)** REF JJA Internal  
Variability  $\delta \bar{f}^{\text{JJA}}(\mathbf{r}|\Omega_i)$

